A PROPOSED DIFFERENTIAL OMEGA SYSTEM

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THESIS

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ABSTRACT

Omega is a long range electronic navigation system which utilizes phase difference measurements between signals received from two transmitting stations to determine a line of position. The major cause of inaccuracy in the system is the propagation anomalies of the Omega signals. Differential Omega is based on the theory that throughout a small geographical region the phase difference errors caused by these anomalies are identical. A monitor site might be established within this area which would determine the extent of the error and relay this information to other users. It is the purpose of this thesis to present and test a workable Differential Omega system which utilizes a Coast Guard radiobeacon as a monitor site and the modulated radiobeacon signal to transmit the correction information.

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I. INTRODUCTION

The problem of navigation has been the main concern of seafarers since the beginning of time. The requirement for an accurate global all weather navigation system has become even more critical during the present era with the advent of high speed surface vessels, jet aircraft and nuclear submarines. The ultimate navigation system must satisfy each of the following requirements: long range, accuracy, reliability and flexibility. Its range must cover the entire globe with special consideration given to those areas where maximum usage is expected. The accuracy obtainable from such a system must be at least that required by the most stringent of its users. The system must be usable throughout the entire twenty-four hour day and during all weather conditions. It must be flexible and inexpensive in order to adapt to both civilian and military user requirements.

As the search for the ultimate navigation system progressed it became increasingly apparent that it is impossible for any one system to satisfy all of the imposed requirements. Electronic navigation systems were limited in range and/or accuracy, adverse weather conditions precluded the use of celestial navigation and inertial systems were too expensive and in addition required an accurate datum point. It was under these concepts and limitations that the forerunner to the Omega Navigation System was devised. With refinements, this system was thought to approach the ultimate navigation system and hence the name "Omega" (the final answer).

II. OMEGA NAVIGATION SYSTEM

A. DEFINITION

The Omega Navigation System is a long range, low frequency, electronic navigation system which utilizes phase difference measurements between signals received from two transmitting stations to determine a line of position (LOP). Eight transmitting stations will be located at various positions around the globe with baselines of approximately 5000 nm. Each station transmits in a predetermined sequence a signal of the same frequency (presently 10.2 or 13.6 kHz) for approximately one second. Synchronization of the transmitting stations is accomplished through the utilization of individual cesium beam frequency standards and continuous monitoring [1]. The Omega system is similar to Loran in that they both generate hyperbolic LOP's. Omega accomplishes this by comparing the phases of two incoming CW signals, whereas, the Loran-A system measures the time difference between the reception of two separate pulses.

B. THEORY

The basis of the Omega theory is that electromagnetic signals in the very low frequency (VLF) range exhibit extremely good phase stability over very long ranges. This phenomena and the useful navigation system possibilities it represents were first proposed by Professor J. A. Pierce of Cruft Laboratories, Harvard University. Professor Pierce, who was also one of the developers of the Loran system, suggested using very low frequencies to obtain better accuracy at longer ranges through the increased stability of the propagated signals [2]. This theory was the basis of the Omega Navigation System which was developed and tested by the Naval Electronics Laboratory Center (NELC) [1,3].

C. ADVANTAGES

As is shown below Omega does possess many of the requirements necessary for an all purpose global navigation system which would be acceptable to both the military and civilian users.

1. Global Coverage

The Omega system provides complete global coverage utilizing eight transmitting stations. Since only eight transmitting facilities are required, the operating agency's expenditure of personnel and/or equipment would be reduced as compared to other electronic navigation systems.

2. LOP Redundancy

The eight Omega transmitting stations would theoretically provide 28 LOP's at any point on the earth's surface. Certain factors such as proximity to either the transmitting stations (within 600 nm) or the baseline extensions will, to some degree, inhibit the utilization of particular LOP's in specific areas. Also at a specific location certain LOP's are more accurate and reliable than others due primarily to the Omega signal paths being entirely over water or comparatively homogenous earth areas. The less accurate LOP's have signal paths over relatively nonhomogenous land regions, ice areas, etc. which alter the phase velocity of the Omega signal and hence degrade their accuracy. An example being in the California area where signals received from the Aldra, Norway Transmitting Site are all but unusable due to the signal path transversing the Greenland ice pack.

The planners of the Omega system predicted that at any receiving point at least five or six transmitting stations would provide signals which fully satisfy system standards for accuracy and reliability [3]. This built in redundancy permits the user to select from the most accurate and reliable of the Omega LOP's available, those which afford the most optimum crossing angles. It is also possible to obtain an Omega position fix even if the service of one, or even two, of the transmitting stations are interrupted by technical difficulties or extreme propagation anomalies.

3. Accuracy

The degree of position fix accuracy obtained from the Omega system is still in question with exact figures dependent upon which reference publication is consulted. Stated values of Omega rms position fix error range from 0.5 to 1.0 nm during the daytime and 1.2 to 2.0 nm at night [1,4].

4. Reliability

The Omega system will remain operational yielding acceptable results throughout all weather conditions with the exception of periods when extreme sudden ionspheric disturbances (SID) occur.

D. DISADVANTAGES

The Omega system does have two serious deficiencies which tend to degrade its performance; the lane ambiguity problem and signal propagation delay variations.

1. Lane Ambiguity

The phase difference readings of each pair of stations go through 360 degrees every half wavelength along the baseline and then repeat themselves. This results in a lane ambiguity situation, in which, the individual lanes are approximately eight nm wide on the baselines at 10.2 kHz [2]. Therefore, to obtain an Omega fix a user must know not only the LOP phase readings but also the specific lane in which he is operating. To determine which lane the user is in an estimate of his position with $\pm$ four nm is required. This inherent system problem may be solved by the utilization of automatic lane counters or the use of additional supplementary Omega frequencies. The second method involves the generation of a frequency of 13.6 kHz in addition to the basic frequency of 10.2 kHz. The substraction of these two frequencies yields a frequency of 3.4 kHz which has a larger lane width (24 nm) on the baseline permitting the user a greater margin of error in his initial estimate of position. Additional frequencies would be added to further increase the lane width.

2. Variation in the Signal Propagation Delays

This deficiency in the Omega system is more serious than the lane ambiguity problem in that it affects the system accuracy. If the

Omega signals are unpredictably delayed between the transmitter and the user's receiver a faulty phase reading and hence LOP will result. Such signal propagation delays are caused by ionsphere shifting, nighttime fluctuations, SID's and variations in the terrain over which the signal transits.

a. Ionsphere Shift

The Omega signal propagates in what is known as the "Earth-Ionsphere Waveguide."[1] The upper dimension of this waveguide (ionsphere height) varies between daytime and nighttime conditons. This diurnal shifting of the ionsphere causes variation in the phase velocity of the Omega signals which result in large but fairly predictable errors in the Omega phase readings. These errors have been studied carefully and the results tabulated. Precomputed Omega corrections for a specific geographical area may be obtained which are utilized in the same manner as Loran skywave corrections [5].

b. Small Scale Variations

These random fluctuations in the phase readings usually occur at night and are very unpredictable.

c. Sudden Ionsphere Disturbances

These disturbances are caused by either or a combination

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[1] Pohle, C. G., "The Omega System of Global Navigation," <u>USCG, The Engineer's Digest</u>, v. 152, p. 26-33, July-August-September, 1966.

of solar flares, magnetic storms or high altitude nuclear bursts. SID's occur infrequently and with the exception of those caused by nuclear explosions are very unpredictable. Solar flares cause a reduction in the upper dimension of the Earth-Ionsphere Waveguide (ionsphere height) which results in an increase in the Omega signal phase velocity. This velocity increase causes an inaccuracy in the Omega phase at the user's position [6]. The average SID might take five to thirty minutes to achieve an intensity which disrupts the Omega system. A large SID is capable of producing a maximum fix error in excess of three nm which usually decreases to zero nm in two to three hours [7].

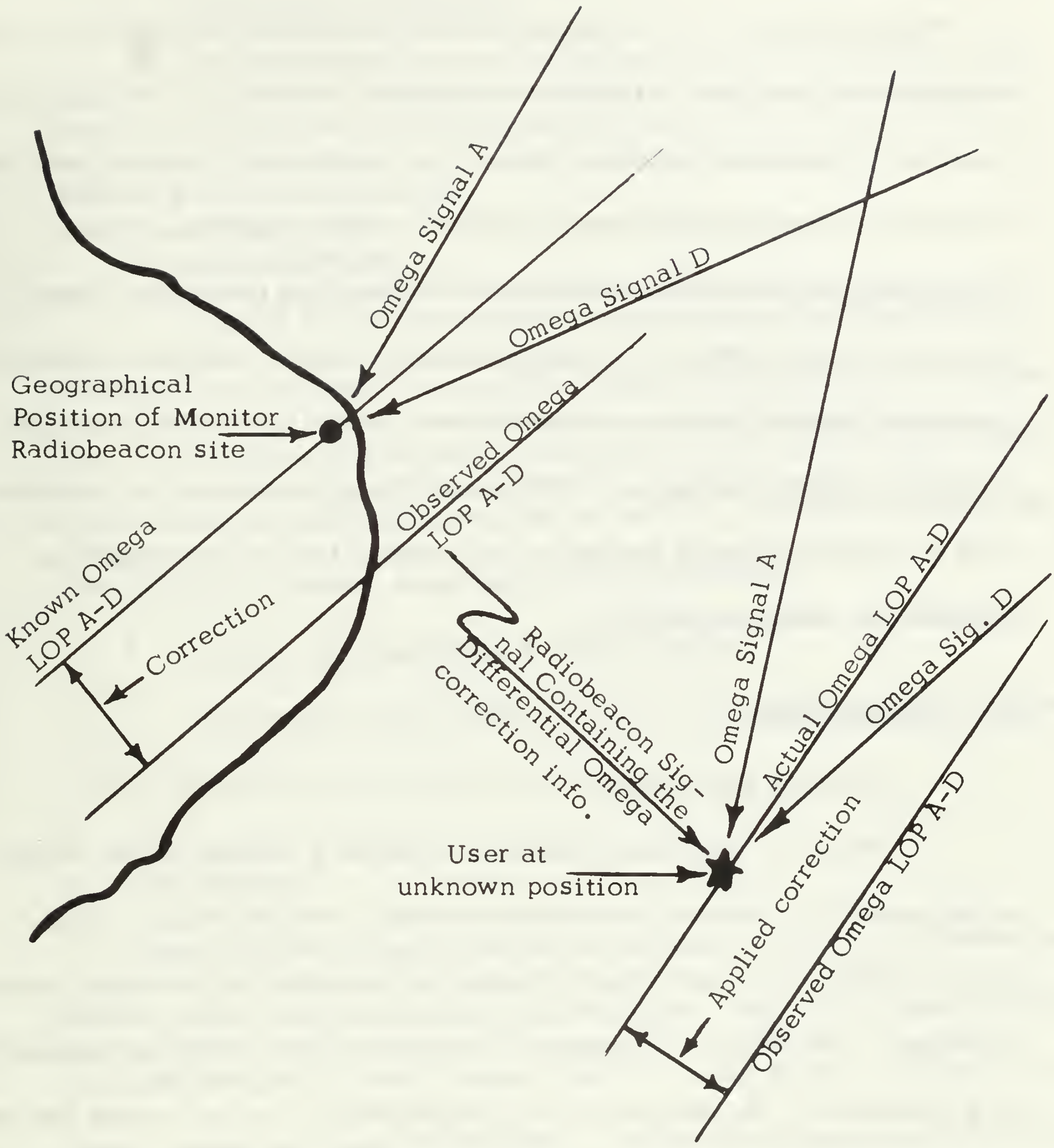
d. Signal Path

Certain propagation delays are caused by the type of earth surface (land, water, ice, etc.) over which the Omega signal transits between transmitter and receiver. The errors caused by this type propagation delay may be partially reduced by calculations at the monitor sites to determine corrections to the hyperbolic LOP's. Seasonal variations make correctional estimates difficult. An example of seasonal variation is the North Atlantic Ocean where the summer transit path is over unfrozen sea water whereas the winter propagation path is over ice.

III. DIFFERENTIAL OMEGA

It was due to the unpredictable propagation delays and the inaccuracies thus caused in the Omega LOP's that the concept of Differential Omega was born. This idea was first formally proposed in 1966 by the Omega Impletation Committee, which was set up under the auspices of the Department of the Navy [3].

Differential Omega is based on the premise that within the Differential Omega region (a circle with a radius of 250 to 300 nm) the phase difference error of the Omega signals caused by the various path delays and local noise conditions would affect all user's receivers to the same degree. A reference (monitor) site whose position and true Omega phase difference readings are known is then selected. Omega phase observed at the monitor site at any instant is compared to the true known value and a correction (plus or minus) is determined. Since any other user in the Differential Omega region is affected in the same manner as the monitor, the user could apply this correction to his observed Omega reading to get his corrected Omega reading. Some method of communications which is reliable, inexpensive, quick and accurate must be found to transmit the correction reading from the monitor to the user. It has been proposed that a Coast Guard radiobeacon be used as the monitor site and a modulated radiobeacon signal be utilized to transmit the correction information [8]. It will be the purpose of this thesis to present a Differential Omega system for a major United States port which utilizes a radiobeacon as the communications link. Figure 1 illustrates this type Differential Omega system.



(1) The incoming Omega signals are monitored at the radiobeacon site and values are compared to the known true reading. Any difference (or discrepancy) noted in the comparison constitute a correction signal and is used to modulate the radiobeacon signal.

(2) The vessel monitors the incoming Omega and modulated radiobeacon signals. The navigator determines the correction from the demodulated radiobeacon signal. This is applied to the vessel's Omega reading to determine the actual Omega line of position.

PROPOSED DIFFERENTIAL OMEGA CONCEPT

Figure 1

A. ACCURACY

The significance of navigation accuracy is a relative matter, what is acceptable to one user is totally unacceptable to another. The degree of accuracy in midocean operating areas is not particularly critical (with the exception of special duty vessels such as missile launching ships, oceanographic ships and ocean station vessels) and the normal Omega accuracy should suffice. The requirement for a more accurate electronic navigation system becomes paramount as a vessel approaches land and especially harbor entrances. Differential Omega increases the accuracy over the ordinary Omega results on the order of five to one within the Differential Omega region [9].

B. APPLICATIONS

1. Terminal Navigation

The most hazardous portion of a vessel's journey occurs within a 100 miles of its arrival or destination point. The proximity to land, greater traffic load and efforts to arrive on schedule are the major sources of danger. The ability of commercial vessels to meet operating schedules is a necessity. The delay cost for a supertanker stuck in a thick fog can be exceedingly high. Inclement weather with its reduced visibility conditions further complicate the situation.

This merging traffic problem at the outer harbor entrances could be alleviated through the establishment of sea lanes in much the same manner as automobiles are funneled into a major freeway. To make the concept of sea lanes practical some quick, reliable and accurate method of determining the vessel's position must be found.

2. Large Harbor Navigation

The requirement for a large harbor electronic navigation still exists. Loran-B was intended to provide this service but was never actually put into commission.

3. Air-Sea Rescue

Most of the search and rescue operations involving maritime accidents and mishaps occur within a nominal distance from the shore line. An accurate navigation system would provide positioning information for both the distressed and rescue vessels, thereby increasing the likelihood of a speedy, successful rescue operation.

4. Coastal Oceanographic & Cable Laying

Both types of work require accurate, reliable position information to accomplish their respective missions.

C. ADVANTAGES

Many of the existing electronic navigation systems could adequately perform some of the applications listed above. But all of these systems have deficiencies in one or more of the following areas: accuracy, expense, speed and range capabilities. Differential Omega performs the above applications with good results and in addition has the following advantages:

1. Differential Omega Receiver

The reception of a Differential Omega signal is the same as the reception of an ordinary Omega signal. This permits the obtaining of midocean position fixes with ordinary Omega accuracy and more accurate fixes within the Differential Omega region utilizing the same piece of equipment (the Omega receiver).

2. Simplicity & Speed

Once the user obtains his Omega and correction readings, the corrections are applied and the resulting LOP's are plotted to obtain a fix. The total time required to obtain a Differential Omega position fix is only slightly greater than for an ordinary Omega fix.

3. Sudden Ionspheric Disturbance Warning Service

Differential Omega enables the user to quickly establish the fact that the Omega system is unusable due to an SID. It will also determine when the SID's effects have diminished to an extent that the system is again usable. It is also possible using the Differential Omega to minimize the error caused by SID's and allow the system to be used during at least a portion of the SID period.

D. RESULTS OF FEASIBILITY TESTS

There have been a number of evaluation and feasibility studies performed on the Differential Omega concept to determine its actual performance characteristics [9, 10, 11, 12, 13]. All of the evaluation reports are in agreement that Differential Omega does live up to its stated objectives and capabilities, although there is some discrepancy in the actual performance figures.

1. Accuracy

Reference 9 states that the average Omega sky wave corrected LOP error was typically 5-15 centicycles (cec) during the daytime and

10-35 cec at night.[2] It further states that by operating differentially at separation distances of 25-225 miles the average position line error was reduced to typical values of 1-3 cec during the day and 4-7 cec at night. The results demonstrate an improvement factor of five to one. The values above are in slight disagreement with those listed in Ref. 11, which are an average rms error for skywave corrected Omega LOP's of 1.5 cec during the day and 5 cec at night. By operating differentially at separation distances of 100-300 miles this reference states a daytime rms error of less than 0.5 cec and at night 1.0 cec. The improvement factor for this feasibility test was four to one.

2. <u>Range</u>

All evaluation tests used an upper limit for the Differential Omega region of between 225 to 300 nm. This upper limit is the cutoff point where Differential Omega results are not appreciably better than ordinary Omega results. Reference 9 states that Differential Omega errors were relatively independent of separation distances. Reference 11, however, is of the opinion that errors increase only slightly as the spacing from the reference monitor was increased from 100 to 300 nm. Also at separation distances less than 100 nm there is an apparent decrease in the error with a decrease in spacing.

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[2] A centicycle is a term which is used frequently in connection with Omega navigation signals. It is defined as one-hundredth of a full cycle of phase change at the frequency under consideration. Therefore one cec at 10.2 kHz equals a LOP displacement of approximately 480 feet on the hyperbolic system baseline.

3. SID Improvement

The results of all the feasibility studies concur that there is a significant improvement in system accuracy when Differential Omega is used during the occurrence of a SID. An example of this occurred on 23 October 1966 during a Differential Omega evaluation study conducted in the vicinity of Austin, Texas. A severe SID caused a Haiku phase error in excess of 40 cec to be noted with ordinary Omega, while Differential Omega with a separation distance of 50 nm reduced this error to approximately five cec [11].

E. ESTABLISHMENT OF A DIFFERENTIAL OMEGA SYSTEM

With the positive results of the preliminary evaluation studies now on record and the approval granted for the construction of the five remaining permanent Omega transmitter facilities, it is only a matter of time until some form of Differential Omega system is established.

1. Cost

In the establishment of a Differential Omega system, which employs a radiobeacon as the communications link, the following expenditures must be considered:

a. Cost to User

To use the system a navigator must have both an Omega and a modified radiobeacon receiver. The required Omega receiver may be any of the existing models on the market. The radiobeacon receiver could be any receiver capable of receiving a modulated signal (carrier frequency 250 to 300 kHz) that has been modified to provide a demodulation capability.

b. Cost to Operating Agency

The cost to the agency which establishes and maintains a Differential Omega system would be minimal and may be divided into initial installation cost, maintenance expenditures and personnel requirements.

(1) Initial Installation. The system would utilize the existing Omega and Coast Guard radiobeacon systems. Only the installation of the monitor Omega receiver, interface equipment and minor modifications to the radiobeacon transmitter would be necessary at the monitor site. Design of interface equipment and the radiobeacon modifications will be discussed in Section IV.

(2) Maintenance Expenditures. Only routine corrective and preventative maintenance should be necessary at the monitor site. This could be accomplished by the radiobeacon station personnel if they were trained prior to their reporting on board. The only major maintenance problem foreseen would be a malfunction to the Omega monitor receiver. A replacement unit could be installed in a standby condition and repairs to the faulty receiver accomplished at an electronic repair facility.

(3) Personnel Requirements. Since the Differential Omega equipment at the monitor station is fully automated there would be no requirement for a continuous watchstander. The only personnel necessary would be the radiobeacon station complement to perform routine maintenance and calibration checks.

2. Coverage Region

The initial step in the establishment of a Differential Omega system is the selection of an area to be covered. The Differential Omega concept offers no advantages to the phase reading of a specific LOP within a region located 600 nm from that specific Omega transmitting site. When the Omega system becomes fully operational with eight transmitting stations this limitation should not present any difficulties due to the system redundancy. It will be assumed in the establishment of this hypothetical Differential Omega system that the eight transmitter facilities are already operational. In the selection of a port region to be covered the primary considerations must be the amount of shipping traffic and the expected weather conditions. To make the system economical and to insure continuous monitoring the port chosen must be heavily used by both military and civilian shipping. Another factor in the selection of a port should be that the weather conditions of the specific area be inclement during a portion of the year. These conditions for the selection of a port would become less important as more Differential Omega systems are established. The ports that should be considered for the initial system are New York, Boston, Baltimore, Norfolk, Seattle and San Francisco. Of these choices the Port of New York was chosen due to its extremely heavy traffic load and occasional reduced visibility conditions. It should be noted that it is entirely possible to include an additional monitor site to provide an "overlap condition" in which, for example Boston, New York, Philadelphia, Baltimore and the Norfolk region might be covered by two or three Differential Omega regions.

Once the Port of New York is chosen a radiobeacon facility must be selected for a monitor site. The requirements for this monitor site are: it must be centrally located, free of obstructions which might interfere with the Omega signals and must be easily accessible for any maintenance problems which might arise.

Ambrose Light Structure, located at the entrance of the approaches to New York Harbor, satisfies all these requirements. Aside from the modifications to the radiobeacon transmitter the only other alteration necessary to make this facility a Differential Omega monitor site would be to increase the radiobeacon's range from its present capability of 100 nm to at least 250 nm. Figure 2 is a chart of New York Harbor, indicating the location of Ambrose Light Structure, the extent of the usable Differential Omega region and a proposed sea lane configuration.

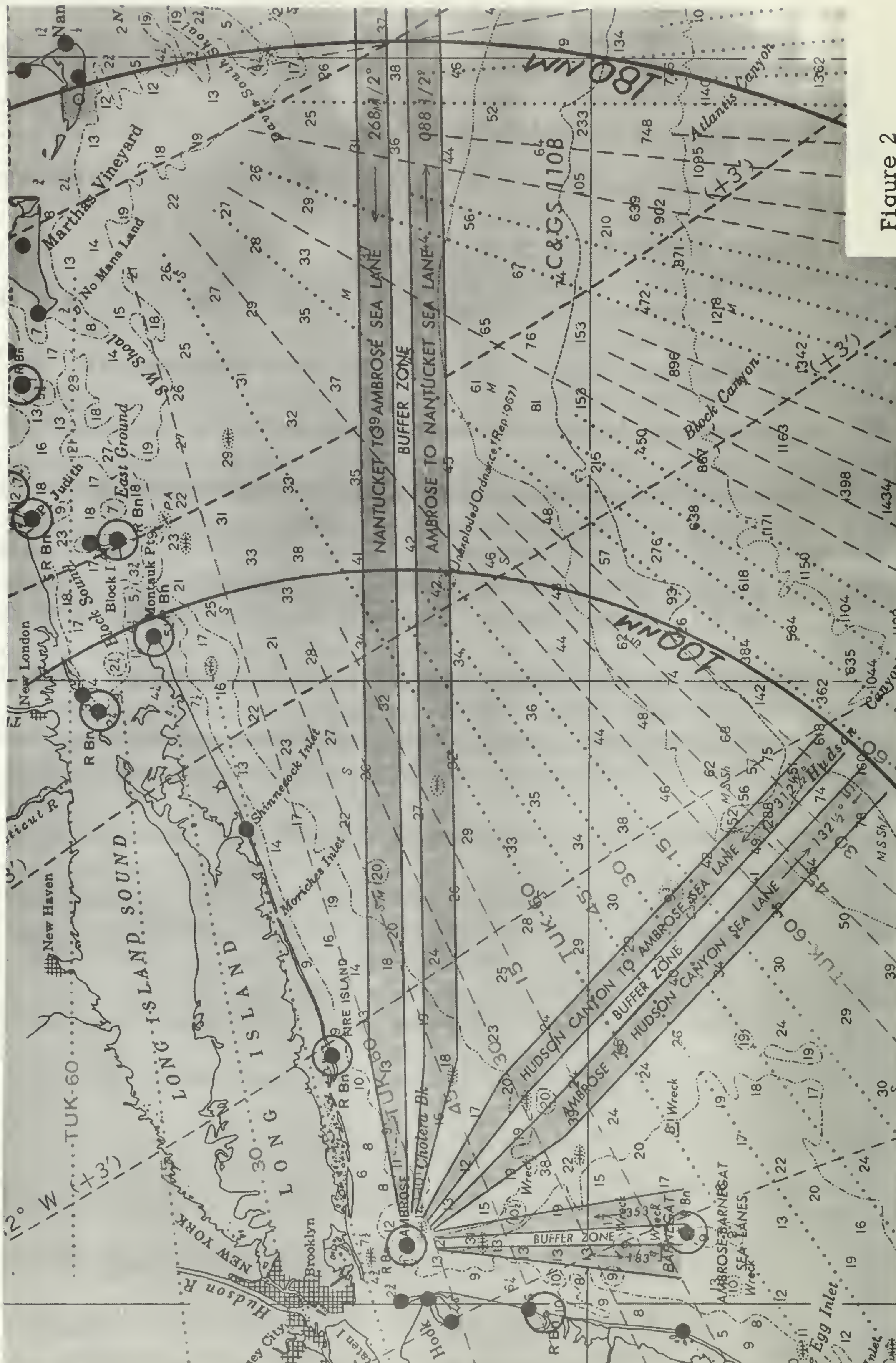

NANTUCKET TO AMBROSE SEA LANE
BUFFER ZONE
AMBROSE TO NANTUCKET SEA LANE
HUDSON CANYON TO AMBROSE SEA LANE
BUFFER ZONE
AMBROSE TO HUDSON CANYON SEA LANE
AMBROSE-BARNEGAT SEA LANES
BUFFER ZONE
100 NM
180 NM
C&GS 1108
TUK-60
LONG ISLAND SOUND
LONG ISLAND
Martha's Vineyard
No Mans Land
East Ground
Block I
Montauk Pt
New London
New Haven
NEW YORK
Brooklyn
Jersey City
Hudson R
Staten I
Shinnecock Inlet
Moriches Inlet
FIRE ISLAND
AMBROSE
BARNEGAT
Cholera Bk
Block Canyon
Atlantis Canyon
Hudson Canyon
Unexploded Ordnance

Figure 2

IV. DIFFERENTIAL OMEGA COMMUNICATIONS LINK

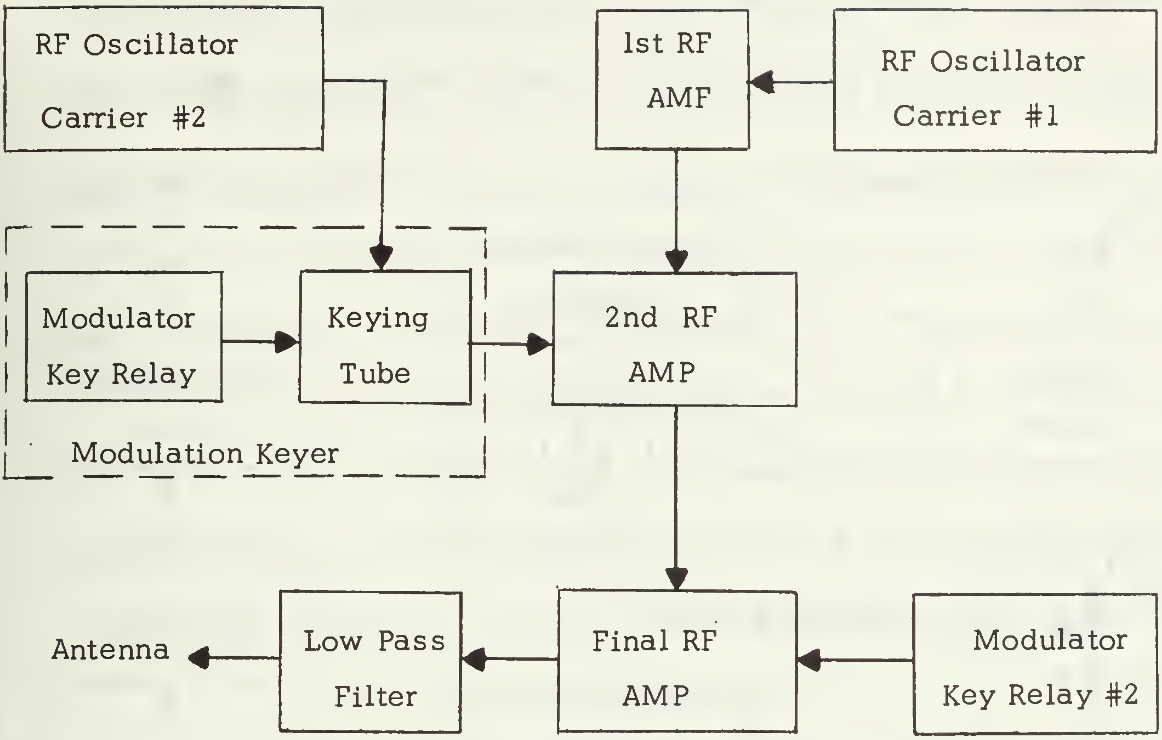
An essential requirement of the Differential Omega system is its ability to rapidly and accurately communicate the correction information from the monitor site to the user. Any radio communications system capable of performing this mission might be employed but certain considerations, such as cost, time delay for initial construction and scarcity of available frequency spectrum dictate that an established system would be the logical choice. The availability and adaptability of the Coast Guard radiobeacon system make it an ideal selection to serve as the communications link.

A. RADIOBEACON

Radiobeacon installations are located on all United States coastlines with concentrated coverage surrounding major port areas. Usually three to six individual radiobeacons of a specific territorial region are netted together operating at the same frequency. Each of the radiobeacons in a specific net are cycled to transmit in a predetermined sequence for a one minute period and then remain silent for the remainder of the cycle. It would be within the one minute on period that the Differential Omega monitor's radiobeacon must transmit the correction information.

1. Transmitter

The transmitters presently being used in most Coast Guard (CG) radiobeacons are crystal controlled with a broadband untuned output. A low pass filter is inserted after the final RF amplifier to reduce any harmonics present to an acceptable level [14]. The transmitter requires no tuning with the only adjustment available being for desired output power. (The maximum range for CG radiobeacons is presently 125 nm. This would have to be increased to at least the maximum range of the Differential Omega region.) The radiobeacon transmitters employ a "dual carrier" concept which utilizes two crystal oscillators separated in frequency by 1020 Hz. These two separate carriers are added together and their combined output is radiated thereby producing in the receiver conventional AM operation but requiring only one half the bandwidth [14]. In addition to the dual carrier concept a keyed carrier process is utilized. This is accomplished by permitting carrier no. 1 to transmit continuously during the radiobeacon's one minute on period and carrier no. 2 to be keyed intermittently during that period by a coder to produce a morse code letter identifier for that specific radiobeacon. Figure 3 is a block diagram of a Radio Transmitter, Type T-854/FRN, presently being used in most CG radiobeacon installations, which has been set up for "dual carrier" operation. As shown in the following figure, the two individual carriers are added together in the second RF amplifier. The modulation keyer serves to turn carrier no. 2 on andoff to produce the morse code identifier. The modulator key relay #2 switches the radiobeacon on for its one minute period and then off for the remainder of the cycle.



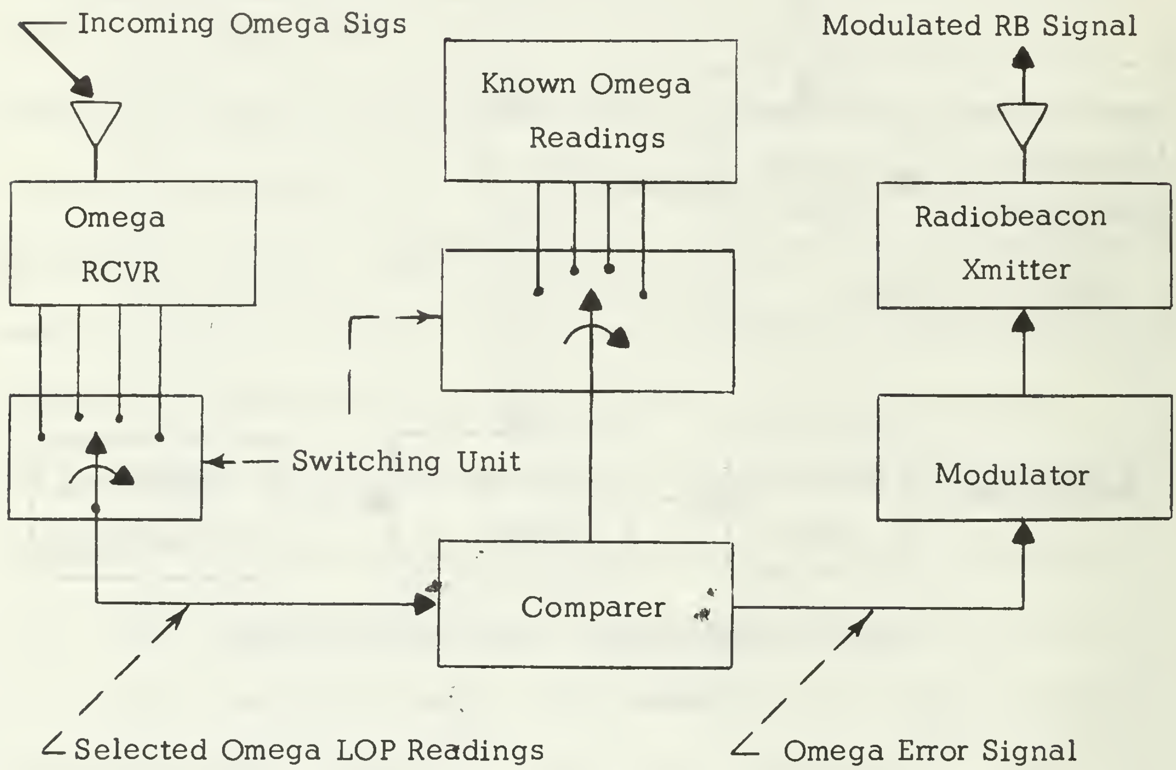
RADIO TRANSMITTER - Type T854/FRN [14]

Figure 3

2. Proposed Modulation Methods

In order to utilize the radiobeacon signal to convey the Differential Omega correction information from the monitor site to the user some method of modulating this signal must be employed. A block diagram of a proposed Omega monitor site is illustrated in Figure 4.

The modulation of the radiobeacon signal should not be accomplished in any manner that noticeably disrupts the regular direction finding service to the non-Omega user. Also the inherent limitations of the existing radiobeacon transmitter/antenna, the requirements of the correction information to be relayed and the frequency spectrum limitation preclude many of the modulation method which might be employed.



DIFFERENTIAL OMEGA MONITOR SITE

Figure 4

a. Continuation of the Dual Carrier Concept

Utilization of the dual carrier concept to relay the correction information in much the same manner as the morse code identifier is now transmitted. The correction information could be coded and transmitted utilizing either morse code characters, a binary coding scheme or a pulse width concept. If the pulse width concept is adopted carrier no. 2 must be energized for a length of time which is proportional to the error correction term.

Ease of implementation using existing facilities and low cost are two of the advantages offered by this type of modulation. One of the disadvantages is that the one minute time segment is not long enough for all the station pair correction terms. It is possible to split the correction message into two parts and send the initial terms during the first time period and the remaining correction terms during the next time period. Utilizing this splitting process at least five minutes would be required to transmit the entire correction message to the user. Another disadvantage to this type modulation scheme is the difficulty in manually reading the correction information due to the relatively high data rate.

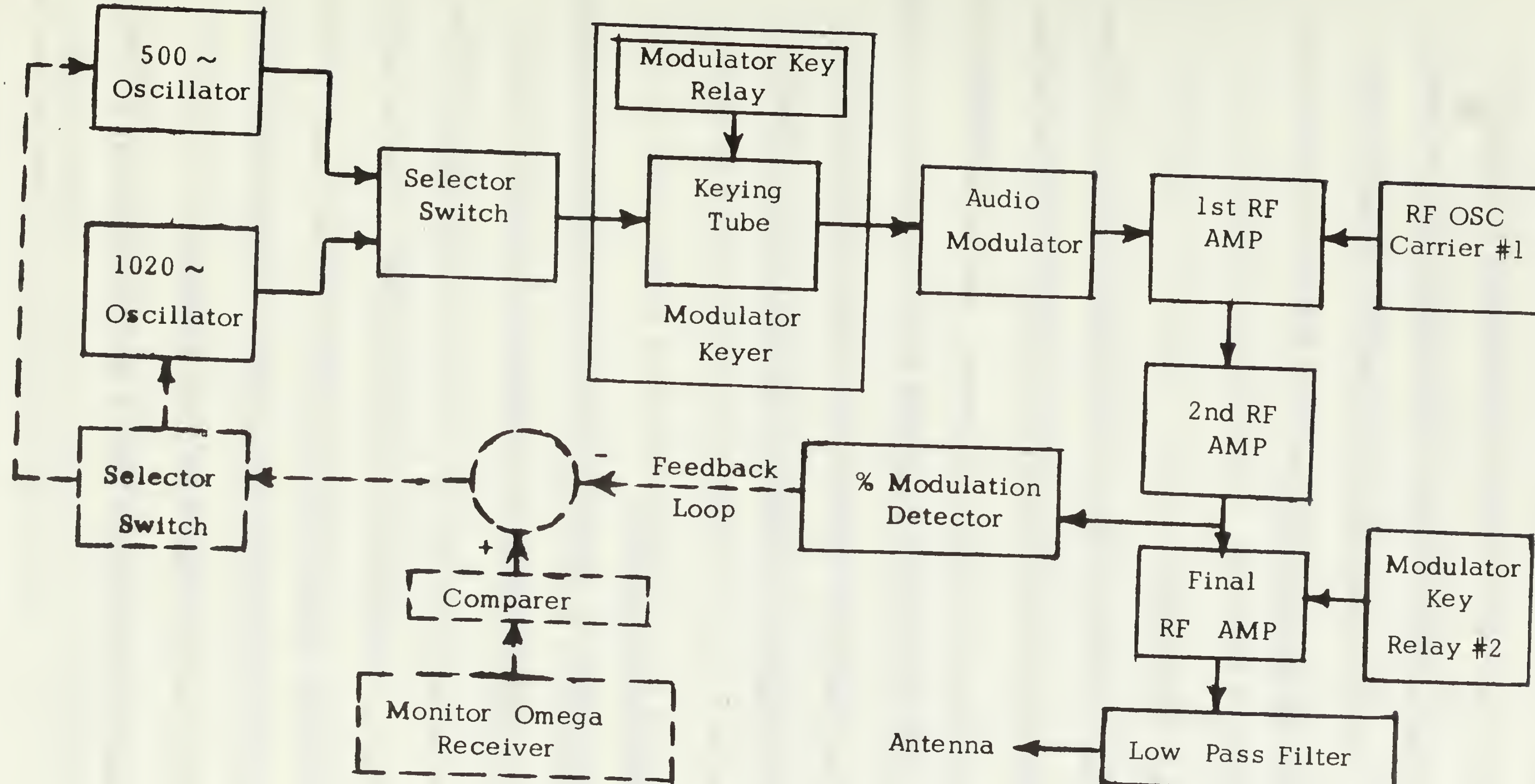
b. Variation of Dual Carrier Concept

If the amplitude of carrier no. 2 is varied in proportion to the monitor's Omega LOP error the correction information could be transmitted utilizing the dual carrier concept without any form of coding. This method would not require any major modifications to the radiobeacon transmitter and would not interfere with the regular direction finding service as long as carrier no. 2's amplitude range was not too large. The main disadvantage of this type modulation method is that major modifications to the user's radiobeacon receiver are necessary in order that the amplitude of carrier no. 2 may be determined. This would at least require special circuitry in the IF section of the receiver. Another disadvantage would be the degree of accuracy which the value of the Omega LOP error could be transmitted and demodulated at the user's position. It would be difficult to stabilize the amplitude of carrier no. 2

to the degree required. Any fluctuation in the amplitude of carrier no. 2 would appear as a change in the correction information even though in actuality none existed. It would also be a rather difficult task to accurately determine the amplitude of carrier no. 2 at the user's position.

c. Amplitude Modulation

In addition to the dual carrier mode of operation the radiobeacon transmitter has the capability to function in a conventional AM mode. The change in modes may be accomplished by disconnecting carrier no. 2's RF oscillator from the modulation keyer (refer Figure 3) and supplying either a 500 or 1020 Hz tone in its place. This audio signal is then fed to an audio modulator where it is amplified to modulate carrier no. 1. Figure 5 is a block diagram representation of an T-854/FRN Radiobeacon Transmitter which has been set up for conventional AM operation. The dashed lines indicate modifications necessary to utilize the monitored Omega LOP error as the controlling parameter for the percent modulation and to incorporate a control feedback loop. To utilize AM to transmit the correction information the percent modulation must be proportional to the Omega LOP error. The percent modulation is controlled by permitting the correction voltage (corresponding to the Omega LOP error) to adjust the amplitude of carrier no. 2 by varying the control potentiometers in either the 500 or 1020 Hz oscillator. This transmitter is capable of amplitude modulating the selected audio tone from 30% up to 70% of carrier no. 1 [14]. The percent modulation detector contained in the radiobeacon transmitter would function in a negative feedback loop as a standard and correction device. The main disadvantage of this



Note: Dashed lines indicate modifications required (1) to use Omega Signal to determine % modulation and (2) to incorporate a self correcting FB loop.

RADIOBEACON TRANSMITTER SETUP FOR AM OPERATION

Figure 5

method of modulation is the difficulty in accurately determing the percent modulation and hence the value of the Omega LOP error. Selective fading especially during nighttime might cause variations in the percent modulation [15]. Another disadvantage of conventional AM is that it would require twice the frequency bandwidth of that necessary for dual carrier operation.

d. PAM, PWM, PCM

Either of these methods are possible and could be adapted. But these methods would require extensive modifications to the existing radiobeacon transmitter and receiver equipment. Another disadvantage of this type modulation would be the excessive amount of frequency spectrum required. The large frequency spectrum requirement would dictate a replacement for the narrow bandwidth radiobeacon antenna presently installed.

e. Frequency Modulation

This type of modulation would provide a quick and accurate method of transmitting the correction information. However, even the utilization of narrow band FM requires a relatively large portion of the frequency spectrum. The bandwidth of the transmitting antenna would probably be too narrow for this type modulation. Another disadvantage is the large amount of modifications that would be necessary to the radiobeacon transmitter, receiver and associated equipment.

f. Amplitude Modulation With a Modulating Signal of Varying Frequency

To utilize this method of modulation the frequency of the modulating signal must be proportional to the Omega LOP error signal.

The amplitude of the modulating signal would be used to transmit the individual radiobeacon morse code identifier. All that would be required at the user's position to obtain the Differential Omega correction values is some method of determining the frequency of the modulating signal. This method of modulation requires a minimum number of modifications to the existing radiobeacon transmitter. The major alteration would be the replacement of the 500 or 1020 Hz oscillator with a voltage controlled audio oscillator (refer Figure 5). This audio oscillator would produce a signal whose frequency would be made to vary in proportion to the Omega LOP error.

This type modulation scheme provides a rapid and accurate method of transmitting the correction information. The number of LOP correction terms which may be handled is limited only by the speed at which the modulating signal's frequency may be determined and recorded. The accuracy of this method is dependent upon the ability to maintain the proper frequency at the transmitter, the magnitude of the scaling factor (LOP error to frequency) and the sensitivity of the receiver's frequency meter.

g. Carrier Separation Modulation

This method of modulation is a combination of AM with a modulating signal of varying frequency and the dual carrier operation. Carrier separation modulation is accomplished by varying the frequency of carrier no. 2 while the radiobeacon transmitter is operating in dual carrier operation. If this variation in frequency is proportional to the

Omega LOP error the Differential Omega correction may be transmitted. This type modulation possess all the advantages of AM with a modulating signal of varying frequency but requires only one half of the frequency spectrum.

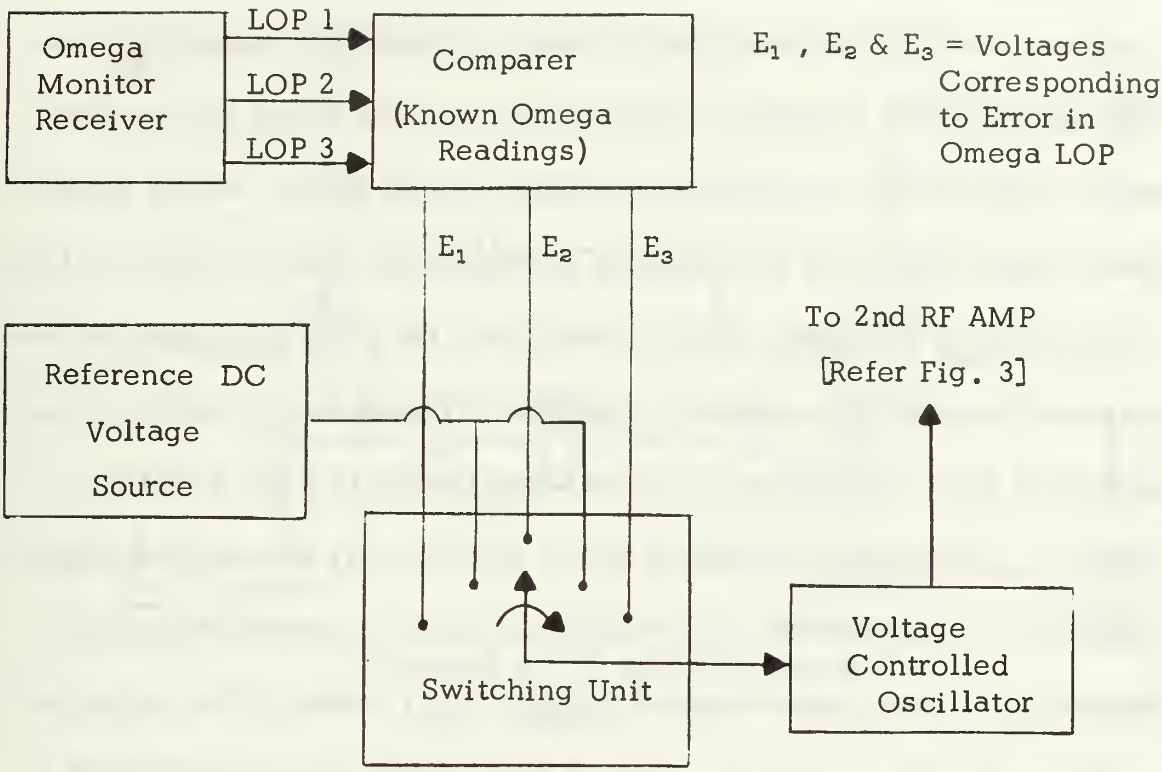
3. Optimum Modulation Method

Of the many modulation methods that are both possible and feasible, carrier separation modulation offers the most favorable possibilities. This method is not only accurate and quick but may be adapted to the present radiobeacon transmitter configuration with a minimum number of modifications. If the variation in the frequency range of carrier no. 2 is not excessively large the regular direction finding service would not be affected. It would not be difficult to identify the monitor radiobeacon's signal from other radiobeacon signals in the net as the monitor's signal would be the only one which did not contain a morse code identifier.

a. Implementation

The frequency of carrier no. 2 may be made to vary in direct proportion to the Omega LOP error voltage through the utilization of a voltage controlled oscillator (VCO). A VCO is a device in which a voltage is utilized as the controlling parameter in determining the output frequency of the oscillator. The VCO concept may be accomplished either by replacing carrier no. 2's RF oscillator in its entirety by a VCO or by modifying the RF oscillator with a voltage dependent capacitor to produce a VCO.

(1) Voltage Controlled Oscillator. Figure 6 is a block diagram demonstrating the method by which a VCO may replace carrier no. 2's RF oscillator to produce carrier separation modulation.



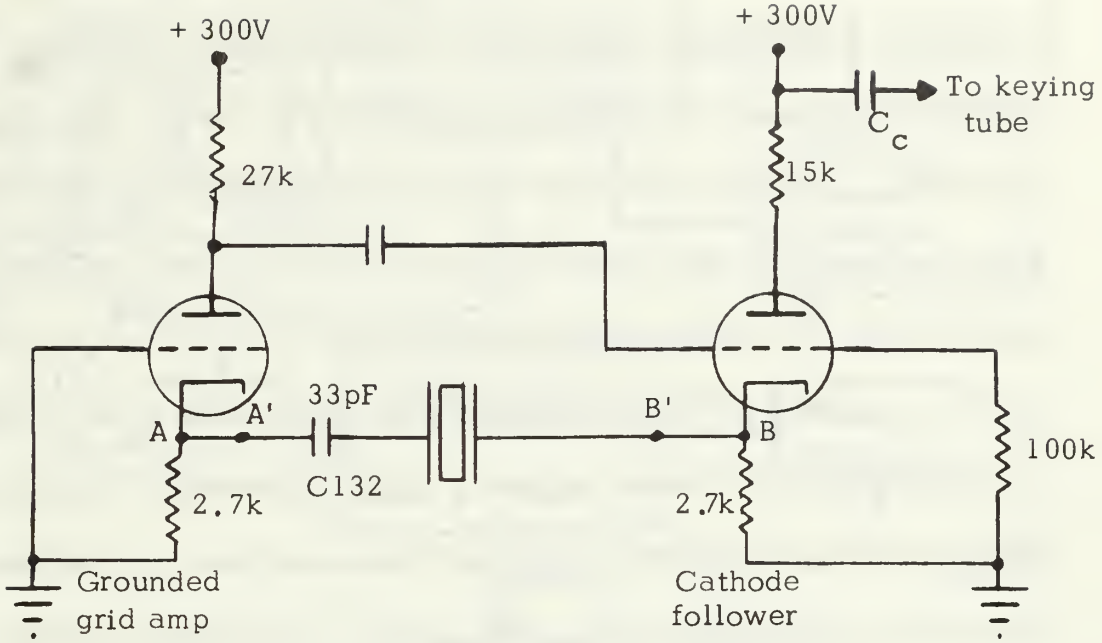
CARRIER SEPARATION MODULATION UTILIZING A VCO AS A REPLACEMENT FOR CARRIER NO. 2 RF OSCILLATOR

Figure 6

(2) Voltage Dependent Capacitor. The crystal presently used in carrier no. 2's RF oscillator is cut so it resonates at the proper frequency when it sees a certain capacitance (33pF). If the circuit presents a capacitance other than this value the crystal will change its oscillating frequency in order that the effective inductance of the crystal resonates with the capacitance presented by the circuit. Figure 7 is a circuit diagram of the RF oscillator used in the radiobeacon transmitter to produce carrier no. 2 [14]. If the value of capacitor, C132, were made

to vary, the oscillating frequency of the crystal would be altered proportionally. One device which may be used to change the capacitance is a voltage dependent capacitor. This device, usually known by its trade name VARICAP, is a reverse biased semiconductor diode. As the reverse bias voltage applied to this diode is increased the depletion region at the p-n junction is enlarged. This is effectively the same as increasing the distance between the plates of a capacitor. Figure 8 is a diagram of the portion of the RF oscillator circuit between terminals A and B (refer Figure 7). This figure illustrates how a VARICAP may be used to replace capacitor C132 to provide the required variation in crystal oscillating frequency. As the reverse biased voltage (V_{DC}), which is the output of the Omega monitor receiver, is varied the capacitance of the VARICAP is changed. Capacitors, C_b, are inserted into the circuit to block the dc bias voltage present at points A and B. This bias voltage is required for the proper functioning of the electron tubes but would interfere with the VARICAP operation. These capacitors are large and present an extremely large impedance to a dc voltage and a small impedance to a RF signal. Resistors R_1 and R_2 are large and serve to isolate the VARICAP from the power supply.

Of the two methods described the insertion of a VARICAP would be the least expensive and easiest to install. The accuracy of either system is dependent upon the stability of the controlled crystal. The only disadvantage of the VARICAP method is the range of output frequencies obtainable.



CARRIER NO. 2 RF OSCILLATOR

Figure 7

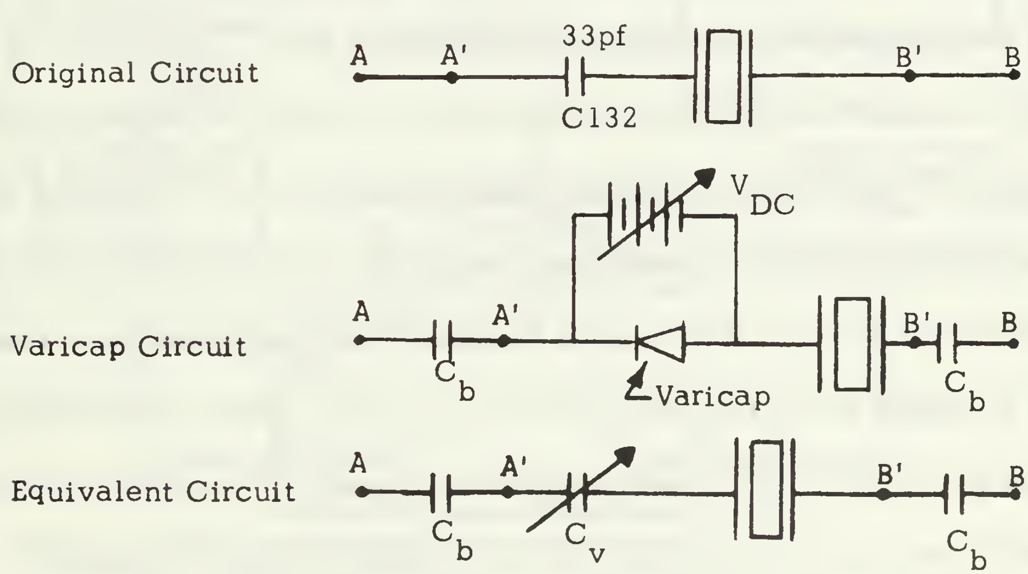
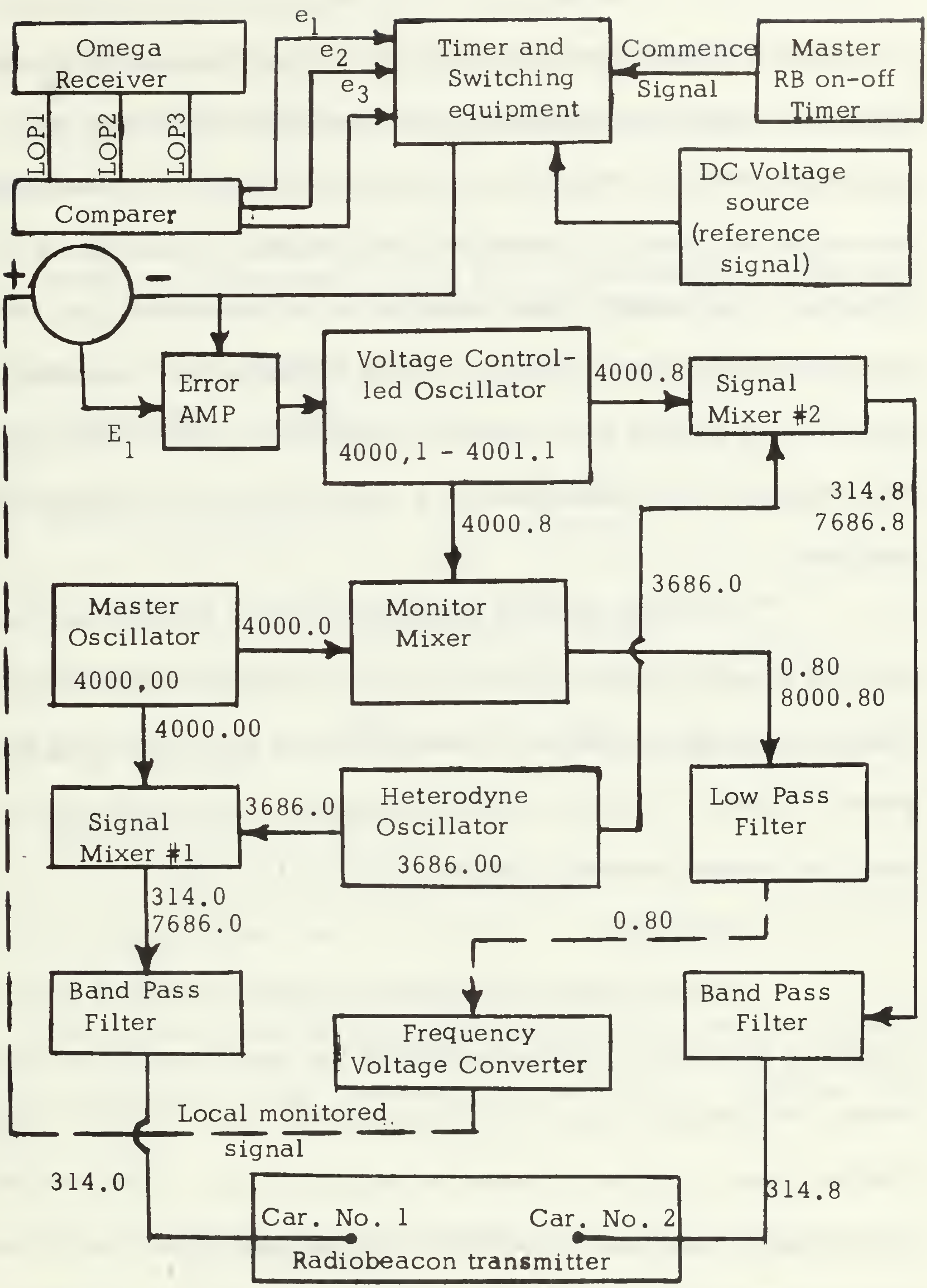


Figure 8

A more sophisticated method of producing carrier separation modulation utilizing a VCO is illustrated by Figure 9. This method incorporates two additional oscillators (a master oscillator and a heterodyne oscillator) and a self correcting feedback loop. The fixed frequency output of the master and heterodyne oscillators are mixed in signal mixer #1 to produce the base frequency of carrier no. 1. Carrier no. 2 is produced by mixing the fixed frequency output of the heterodyne oscillator with the variable frequency output of the VCO. The frequency range of the VCO is predetermined and dependent upon such factors as estimated maximum Differential Omega error, transmitting antenna bandwidth and the receiver's frequency detector sensitivity. The values of the Omega LOP's are compared to the known values (determined from the monitor's position) is a comparer. Any error (e_1, e_2, e_3, etc.) noted is fed through the time unit to both the error amplifier (and thereby indirectly to the VCO) and the comparer in the feedback loop. The outputs of the VCO and master oscillator are also fed to a monitor mixer which produces a signal (local monitored signal) whose frequency is the same as the separation frequency between carriers. This local monitored signal is incorporated in a self correcting feedback loop and is shown in Figure 9 as a dashed line. The error voltage, E_1, is the output of the feedback loop and is used to stabilize and correct the VCO. Band pass and low pass filters are incorporated into the system to remove undesired frequencies which are generated during the mixing processes.

The feedback loop stabilizes and therefore improves the accuracy of the frequency separation between carriers by continuously



Note: All frequencies shown are kilohertz

METHOD OF PRODUCING CARRIER SEPARATION MODULATION

Figure 9

monitoring this separation and correcting for any erroneous VCO fluctuations. In addition this feedback loop cancels any variance in the separation frequency between carriers due to drifting of the master and/or heterodyne oscillators. Drifting of either oscillator will result in the frequency of both carriers being affected to the same degree and should not present any serious problem. Another advantage of this method is that it can be adapted to any specific radiobeacon yielding the correct base frequency by simply switching a single crystal in the heterodyne oscillator.

The values of frequency shown in Figure 9 are the result of a sample Omega LOP error of +20 cec which corresponds to a frequency separation between carriers of 800 Hz (refer to scaling factor shown in Table 1). The hypothetical radiobeacon illustrated in this figure has a base frequency (carrier no. 1) of 314.0 kHz.

b. Accuracy

The accuracy of the carrier separation method of modulation is directly dependent upon the stability of the crystal used in the oscillators. The feedback loop incorporated into the system shown in Figure 9 reduces most of the error caused by oscillator drift. If the oscillator's crystals are of good quality the error in the transmission of the Differential Omega correction term due to crystal instability would be negligible.

The error in the Differential Omega correction terms resulting from a doppler shift in the carrier's frequencies would be negligible. As shown below in the worst possible case situation it would require a relative velocity between the monitor and user of 5.22×10^5 knots to produce an inaccuracy of one cec in the Differential Omega correction information.

Carrier no. 1's frequency: $f_1 = 314 \times 10^3$
Carrier no. 2's frequency: $f_2 = 315.1 \times 10^3$ Hz (For a Differential Omega error of 100 cec. Refer to Table 1.)

Doppler shift in carrier no. 1 = F_{d1}

Doppler shift in carrier no. 2 = F_{d2}

Equation for doppler shift: $$F_d = \frac{V_r fc}{C}$$

V_r = relative velocity between transmitter and receiver

C = speed of light = 1.62×10^5 nm/sec = 5.72×10^8 knots

$$\Delta F_d = F_{d2} - F_{d1} = \frac{V_r f_2}{C} - \frac{V_r f_1}{C} = \frac{V_r}{C} (f_2 - f_1)$$

Rearranging and solving for V_r:

$$V_r = \frac{\Delta F_d \ C}{f_2 - f_1}$$

The minimum value of ΔF_d which could cause a variation of one cec in the Differential Omega correction value is one Hz. Therefore, let $\Delta F_d = 1$ Hz.

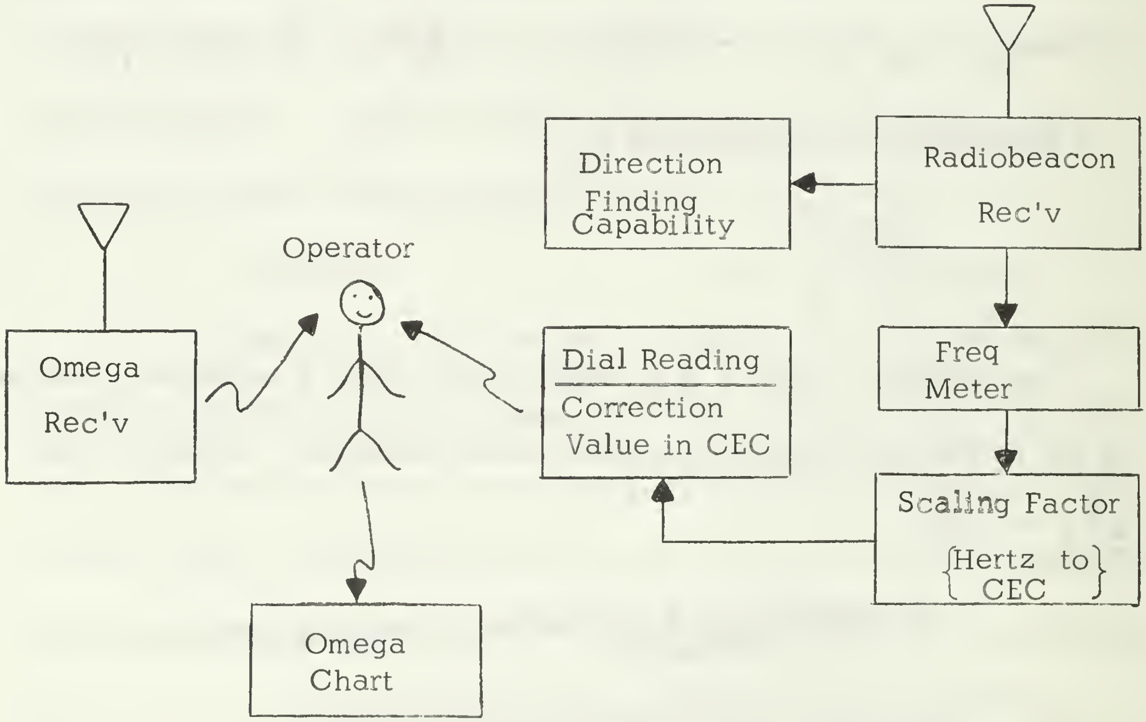
$$V_r = \frac{(1 \text{ Hertz})(5.72 \times 10^8 \text{ knots})}{(1.1 \times 10^3 \text{ Hertz})} = 5.22 \times 10^5 \text{ knots}$$

4. <u>Differential Omega Receiving Installations</u>

The basic equipment required to obtain a Differential Omega LOP consist of a Omega receiver and a radiobeacon receiver which has been modified to provide the capability of demodulating the radiobeacon signal. The process of recording and applying the correction information of the modulation radiobeacon signal may be accomplished either manually or automatically with the aid of a small digital computer.

a. Manual System

The simplest and least expensive Differential Omega receiving system which is ideally suited for smaller units is shown in Figure 10. It consists of the basic equipment (Omega and radiobeacon receivers) mentioned above and utilizes a human operator to record the Omega LOP values, interpret the Differential Omega corrections, apply these corrections and plot the resulting LOPs.

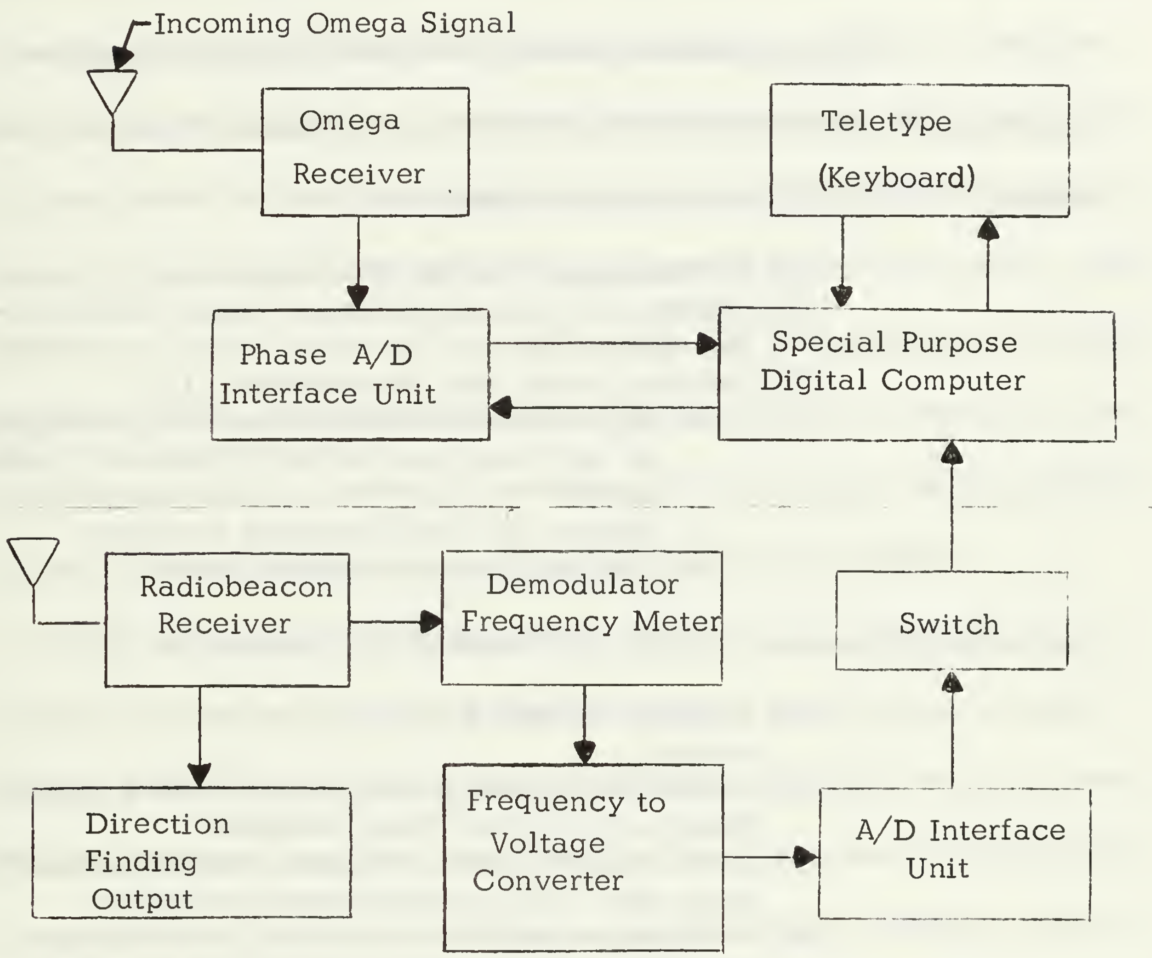


MANUAL DIFFERENTIAL OMEGA RECEIVING SYSTEM

Figure 10

b. Automated System

One of the more elaborate methods of establishing an automated Differential Omega receiving installation is shown in Figure 11.



AUTOMATED DIFFERENTIAL OMEGA RECEIVING SYSTEM

Figure 11

The Differential Omega receiving system shown in Figure 11 may be divided into two systems; a computerized Omega receiving system which is available commercially [16] and the radiobeacon receiving system has been modified to demodulate and recover the correction information contained in the radiobeacon signal. These two systems may be operated independently or they may be combined by closing a switch to provide a Differential Omega capability when operating within a Differential Omega region. The direction finding capability of the radiobeacon receiver is not affected when the two systems are operated in the combined mode.

Communications between the operator and the computer concerning the stored navigation program is accomplished via the teletype keyboard. The navigation program inputs are:

(1) LOP readings from the Omega receiver
(2) Differential Omega correction values from radiobeacon system
(3) Operator inputs from the keyboard [16]
    a. Sky wave correction values when the system is not being used in the Differential Omega mode
    b. Station pair and frequency selection
    c. Time and position initialization

The navigation program outputs displayed on the teletype are [16]:

(1) Position fix data (Lat. Long. to nearest tenths of minute)
(2) Course and speed in degrees and tenths of knots based on averaged Omega readings
(3) Error messages indicating bad receiver data format, noisy data, lane indentification ambiguity
(4) "Difference data" for generating correction or comparison tables for sky wave LOP's versus Differential Omega LOP's

B. DIFFERENTIAL OMEGA CORRECTION MESSAGE

1. Requirements

Regardless of which type radio system is used as the communications link it must satisfy the requirements imposed by the Omega correction message.

a. Length of the Correction Message

In any specific Differential Omega region there is a maximum of 28 LOP's which are available to the user. But in that particular area certain LOP's are more accurate and reliable than others, due to crossing angles and the transit path of the Omega signals. Therefore, of the available LOP's only a select few are usuable in any given region. In most cases the maximum number of usuable LOP's in a region would be eight to ten, of these the best five or six would have to be chosen. The identity of the selected Differential Omega LOP's for an area would have to be published on the Omega charts or in the Notice to Mariners. The Differential Omega correction message must contain the identity of each of the Omega LOP's and the corresponding error information.

b. Monitored Omega Frequency

Since all Omega charts are drawn up utilizing the basic Omega frequency, 10.2 kHz, this is the frequency which would be monitored and error corrections transmitted. If the decision is subsequently made to use 13.6 kHz for better reception in certain areas this information would have to be published or coded into the correction message.

c. Simplicity

It is essential that the Differential Omega correction message be simple in order that it can be accurately and quickly decoded. This must be the case regardless of whether the demodulation process is fully or semi-automated.

2. Form of Differential Omega Correction Information

There are many forms in which the Differential Omega correction information may be conveyed to the user. The two most practical are either the transmission of a latitude and longitude correction or the transmission of the monitor's individual Omega LOP errors.

a. Δ Lat Δ Long Correction

This form involves the transmission of the correction message as a Δ latitude and Δ longitude which could be directly applied to the user's Omega fix position. This would require at the monitor site the plotting of the observed Omega LOP's to obtain a fix. It would also necessitate some sort of weighted decision making capability if the LOP's did not cross in a pin point. The monitor's observed Omega fix position would be compared to its known position and Δ Lat Δ Long generated.

b. Individual LOP Corrections

The monitor's observed Omega readings would be compared to the known Omega readings for the monitor's position and a difference error (cec) for each LOP determined. This difference error and the identity of the individual LOP would be transmitted.

Due to the difficulty in obtaining a position fix and the decision making requirement of the Δ Lat Δ Long method it is felt that the second method mentioned would be easier to implement and more useful to the user.

3. Sample Correction Message Utilizing Carrier Separation Modulation

The range of frequencies over which carrier no. 2 may be varied (and hence the range of frequency separation between carriers) is determined by the transmitting antenna's bandwidth, the maximum value of the Differential Omega correction and the sensitivity of the receiver's frequency detector. The transmitting antenna's bandwidth governs the upper limit of the carrier separation frequency band. Although radiobeacon antennas are not standardized, they all have relatively narrow bandwidths. The maximum width of the carrier separation band is at least 1020 Hz (the frequency separation presently used when a radiobeacon is operating in the dual carrier mode). The minimum width of the carrier separation frequency band is a function of the range of Differential Omega correction values (cec), the scaling factor (cec to Hz) and the receiver frequency detector sensitivity. The maximum expected value of a Differential Omega correction is $\pm$ 50 cec [4]. This value and the maximum carrier separation frequency, which has been arbitrarily chosen for the following example at 1000 Hz, dictate a scaling factor of ten Hz equal one cec. This scaling factor imposes the requirement that the receiver frequency detector sensitivity be at least ten Hz. This would enable the user to possess a capability of detecting a Differential Omega correction value to $\pm$ one cec.

Utilizing the maximum width of the carrier separation frequency band permitted and the maximum value of the correction term expected a Differential Omega correction signal format may be set up as shown in Table 1 and Figure 13.

Differential Omega Correction	Carrier Sep. Mod. Frequency
+ 50 centicycles	100 Hertz
+ 25 cec	350 Hz
00 cec	600 Hz
- 25 cec	850 Hz
- 50 centicycles	1100 Hertz

CARRIER SEPARATION MODULATION SCALING FACTOR

TABLE 1

SAMPLE DIFFERENTIAL OMEGA CORRECTION MESSAGE

Omega LOP	Sample LOP Correction Value	Corresponding Frequency	Signal Format Position
LOP #1	+ 25 centicycles	350 Hertz	F_1
LOP #2	+ 5 centicycles	550 Hertz	F_2
LOP #3	- 30 centicycles	900 Hertz	F_3
LOP #4	- 15 centicycles	750 Hertz	F_4

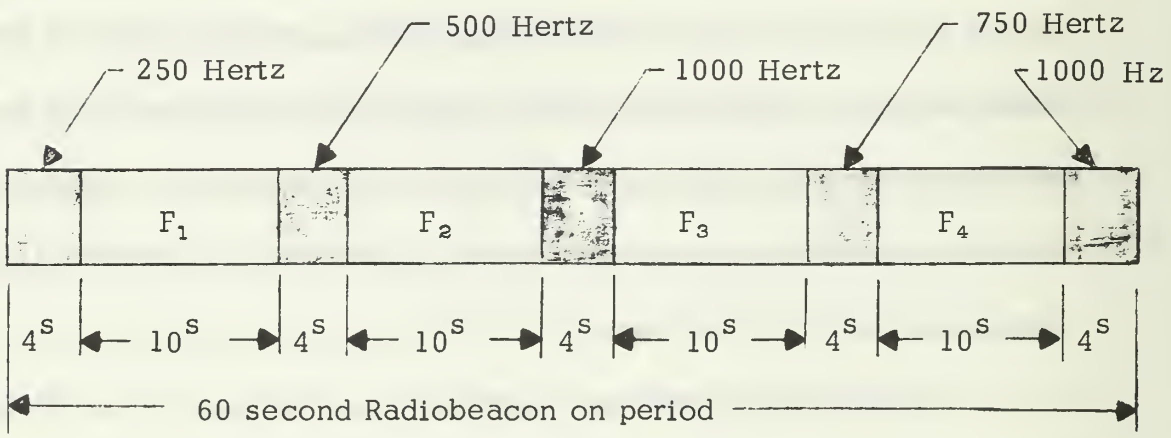


Figure 13

The reference frequencies (250, 500, 750, 1000 Hz) shown in Figure 13 serve not only to separate the correction information frequencies but also as a continuous calibration check for the user's frequency detector. The length of the individual time intervals should be examined during future tests and some optimum values chosen. Tests were performed utilizing the time intervals values shown in Figure 13 and demonstrated that sufficient time was available for the frequency meter movement to settle down and frequency (corresponding to the LOP error term) to be determined.

V. DIFFERENTIAL OMEGA EVALUATION TEST

A Differential Omega evaluation and feasibility study was performed in the vicinity of Monterey Bay, California during the period April to October, 1969.

A. PURPOSE

The purpose of this test was to determine the feasibility of utilizing the differential concept over short separation distances (15-50 nm) and also to evaluate the Differential Omega improvement factor as the separation distances are varied.

B. LOCATION OF TEST OBSERVATION SITES

All of the Omega observation positions were fixed sites whose location are given in Table 2. The Omega monitor site (M) located at USNPGS was designated as the Differential Omega monitor site (which would correspond to the radiobeacon transmitter facility). The other three monitoring sites (R_1, R_2, R_3) correspond to the Differential Omega user's positions. Also included in Table 2 is the separation distance between the Differential Omega monitor (M) and the user's site and the time period during which actual testing was performed.

Site	Location Name	Lat.(N)	Long.(W)	Separ. Distance	Dates 1969
M	US Naval Post-graduate School, Monterey, Cal.	36°35'48"	121°52'22"	0 nm	April thru Oct.
R_1	USCG Light Station, Pigeon Point, Cal.	37°10'54"	122°23'36"	40.2 nm	May thru Aug.
R_2	USCG Light Station, Point Sur, Cal.	36°18'24"	121°54'05"	17.7 nm	Sept. and Oct.
R_3	USN Electronics Lab. Cen., San Diego, Cal.	32°42'29"	117°14'48"		

OMEGA OBSERVATION POSITION LOCATIONS

TABLE 2

C. EQUIPMENT

Table 3 is a listing of the equipment utilized in this evaluation test.

Major Equipment			Site	
Type	Man. & Model	Quan.	Used	Remarks
Omega Rec'r	Tracor Model 599R	2	M, R_1, R_2	Aside from minor bulb replacement no malfunctions were experienced.
Rubidium Freq.Stand.	Varian Mod V-4700	1	M	Long Term Stability = $5x10^{11}$ in any one year period (standard deviation) [17].
Frequency Standard	AN/URQ-9	1	R_1, R_2	Frequency Stability = frequency drift is less than one part in 10^9 per day [18].
Analog Stripchart Recorders	Hewlett/ Packard Mod 7100B	4	M, R_1, R_2	In general two units recording and the other two units being repaired.
Whip Antenna (20 ft.)	Tracor 599-800	2	M, R_1, R_2	

MAJOR EQUIPMENT UTILIZED

TABLE 3

All of the above listed equipment functioned properly with the exception of the analog recorders. Ninty-five percent of the equipment down time was due to a variety of small malfunctions to the ink system and motor bearings within the recorders.

During February, 1969 initial calibration tests were performed on the Omega receivers. These tests were accomplished in two parts, first by feeding actual Omega signals to the receivers from similar antennas located within a foot of each other and second by providing both receivers identical signals from a signal synthesizer. Under no circumstances did the readings from the receivers differ by more than the manufacturer's specified limit (± one cec).

D. DATA

1. Recording

During this evaluation test the phase readings of Omega signals from Trinidad, Forrestport and Haiku were observed. No attempt was made to utilize phase measurements of signals received from the Aldra, Norway Transmitting Station. This was due to the weak strength of the Aldra signal in the Monterey Bay area. At observation positions R_1 and R_2 the phase differences B-C and C-D were recorded for 10.2 kHz and 13.6 kHz. Approximately 100 hours of observations were recorded at the Pigeon Point site (R_1) and 700 hours at the Point Sur location (R_2). Over 100 hours of observations were conducted in collaboration with the Omega monitor site (R_3) at NELC. During this portion of the testing the phase of the Haiku Omega signal was compared to the phase of a signal from a local reference oscillator.[3]

All observations were recorded by analog strip chart recorders which were operated at a chart speed of six inches per hour. At the monitoring sites R_1 and R_2 a continuous 24 hour watch was maintained. The watch-stander was responsible to insure that all equipment was functioning

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[3] Data obtained from test site R_3 was processed at NELC. Results were not available at the time this thesis was completed.

properly and the analog recorders were operating on time. This procedure insured a fairly reliable time synchronization would be maintained between recorders at the different sites. The maximum time discrepancy noted between analog recorders was approximately five minutes.

2. Processing

For the test performed at sites R_1 and R_2 all analog recorder strip charts were manually interpreted and the results digitalized for computer usuage. This operation consisted of sampling the strip charts at ten minute intervals and recording the value on computer cards. There was no editing or smoothing performed on the analog data during the digitalizing process. The strip charts were visually interpreted to an accuracy of $\pm$ one cec.

In addition to the Omega LOP readings the Omega skywave corrections must also be digitalized. The skywave corrections were furnished by NELC for the exact Omega observation positions used during these tests, therefore no interpolation was required for position. These corrections were tabulated on an hourly basis which were usable during a specific two week period. To make the skywave correction sample interval compatible with the interval of the digitalized strip chart readings a linear interpolation of the skywave correction data was necessary. This interpolation provided digitalized Omega skywave corrections with a sample interval of ten minutes.

The digitalized data (strip chart readings and skywave corrections) and associated computer programs were then fed to an IBM 360 Digital Computer for tabulation.

E. RESULTS

1. Parameters Investigated

For each individual Omega LOP the following parameters were determined for both Differential Omega and skywave corrected (SWC) ordinary Omega: Omega LOP error, standard deviation and maximum Omega LOP error.[4]

a. Omega LOP Error

The Omega LOP error was computed at sampling intervals spaced ten minutes apart by utilizing the following equations:

XR = Observed Omega LOP value at R_1 (or R_2)

XM = Observed Omega LOP value at M

YR = True Omega LOP value at R_1 (or R_2)

YM = True Omega LOP value at M

SWC = Omega skywave corrections for R_1 (or R_2)

SWERR = Skywave corrected ordinary Omega LOP error

DOERR = Differential Omega LOP error

---

[4] The unit of measure utilized for the parameters observed was centicycles. A cec as defined by Footnote 2 is one hundredth of cycle at the frequency being considered. At 10.2 kHz one cec equals a LOP displacement of 0.08 nm (480 feet) on the baseline. The Monterey Bay vicinity is close enough to both the Haiku-Trinidad and Haiku-Forrestport baselines that there is no appreciable spreading of these hyperbolic LOP's. Therefore in the Monterey Bay region one cec for either the B-C or C-D LOP's is approximately equivalent 0.08 nm. In utilizing the graphs and tables contained in this thesis the following conversion figures should be applied:

	10.2 kHz	13.6 kHz
1 cec	0.08 nm	0.06 nm
5 cec	0.4 nm	0.3 nm
20 cec	1.6 nm	1.2 nm

$$SWERR = YR - (XR \pm SWC)$$

$$DOERR = YR - (XR + (YM - XM))$$

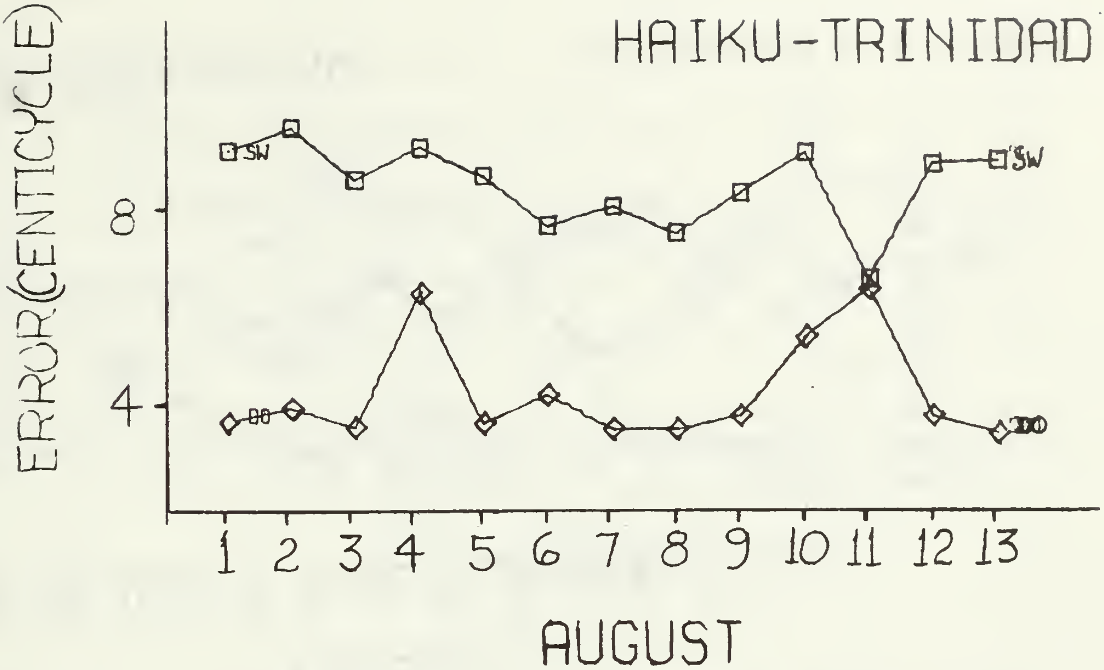
If the absolute value of the Omega LOP error for each ten minute sample were summed and this value divided by the number of samples (144) the result would be an average LOP error for a 24 hour day. Figure 14 is a graph of the comparison of the average Differential Omega daily LOP error and the corresponding average SWC ordinary Omega daily LOP error at site R_1 during the period 1-13 August 1969. It is clearly shown from this figure that during this time period Differential Omega had a smaller average LOP error. Additional average LOP error graphs similiar to Figure 14 but for different sites and/or time periods are contained as Figures 61, 64, 67 and 70 in Appendix A.

b. Standard Deviation

The mean value of the Omega LOP readings for each 24 hour period was determined. From this mean value the root-mean-square deviation (standard deviation) for each ten minute sample interval was calculated. Figure 15 is a comparison of the daily average standard deviation value between Differential Omega and SWC ordinary Omega for site R_1 during the period 1-13 August 1969. Figures 62, 65, 68, 71 of Appendix A are additional graphs of the average standard deviation observed at different sites and dates.

c. Maximum Omega LOP Error

Another important parameter which was determined was the maximum Omega LOP error experienced during each 24 hour period.



SITE PIGEON POINT

COMPARISON DIF OMEGA VS SKYWAVE

COR. AVERAGE ERROR 13.6 KHZ

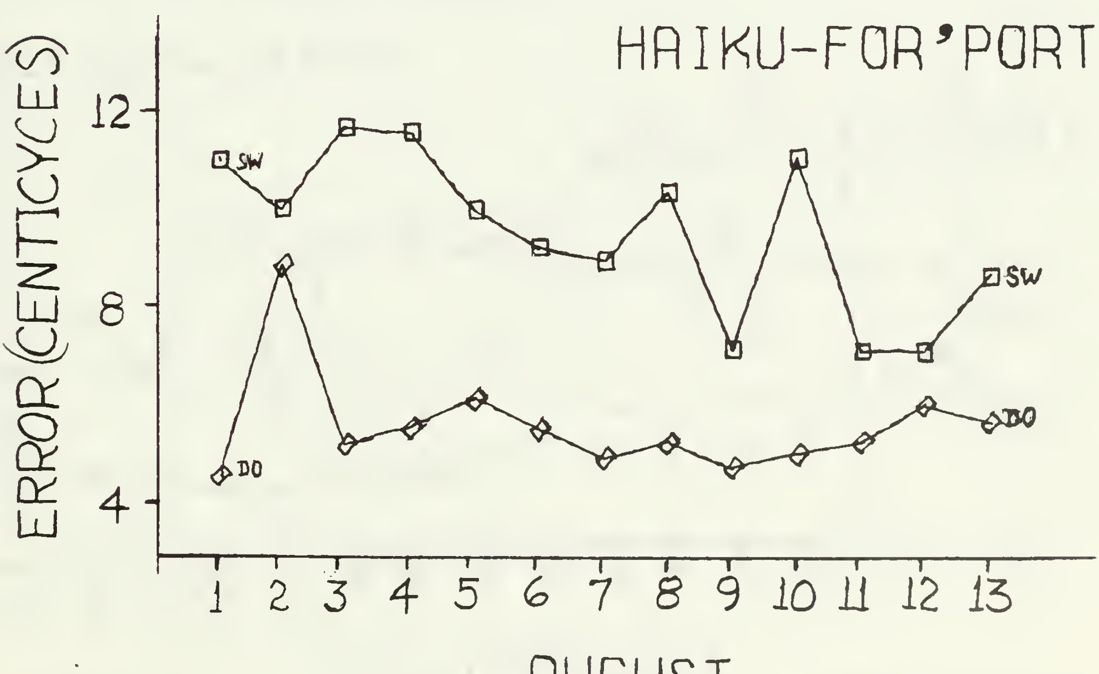
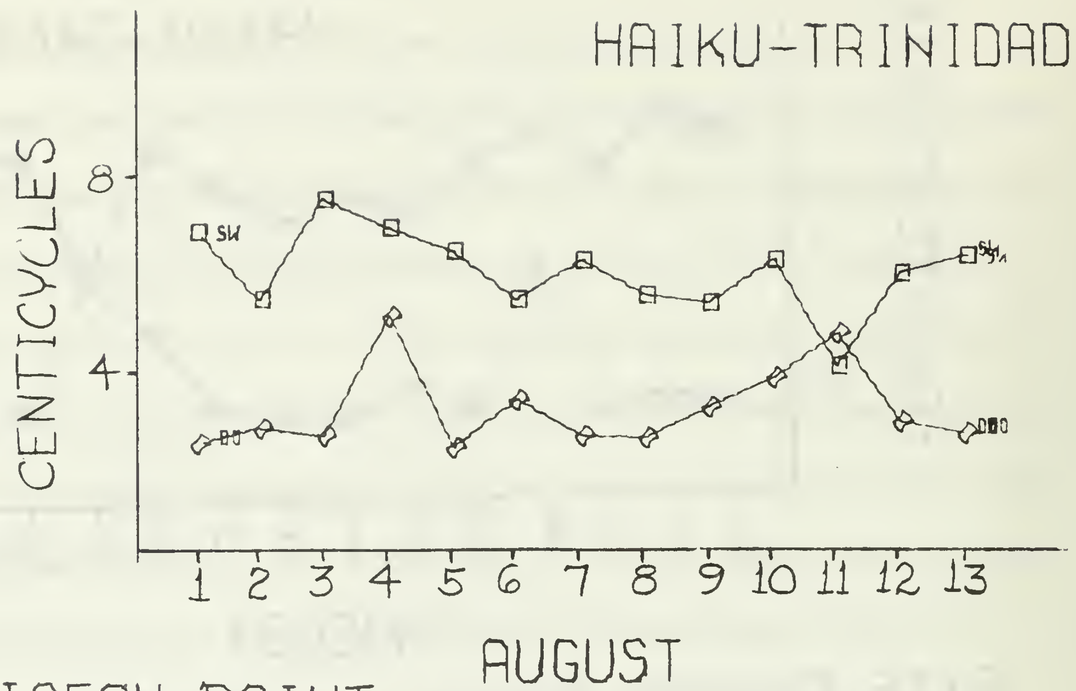


FIGURE 14



PIGEON POINT

COMPARISON DIF OMEGA VS SKYWAVE

CORR STANDARD DEVIATION 13.6 KHZ

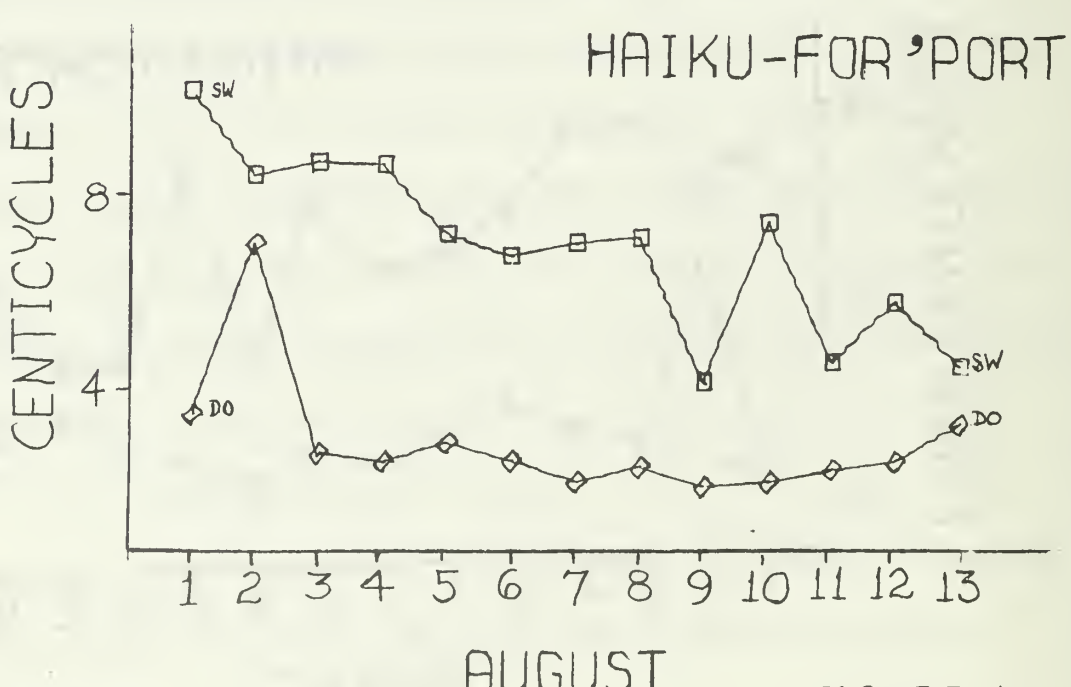
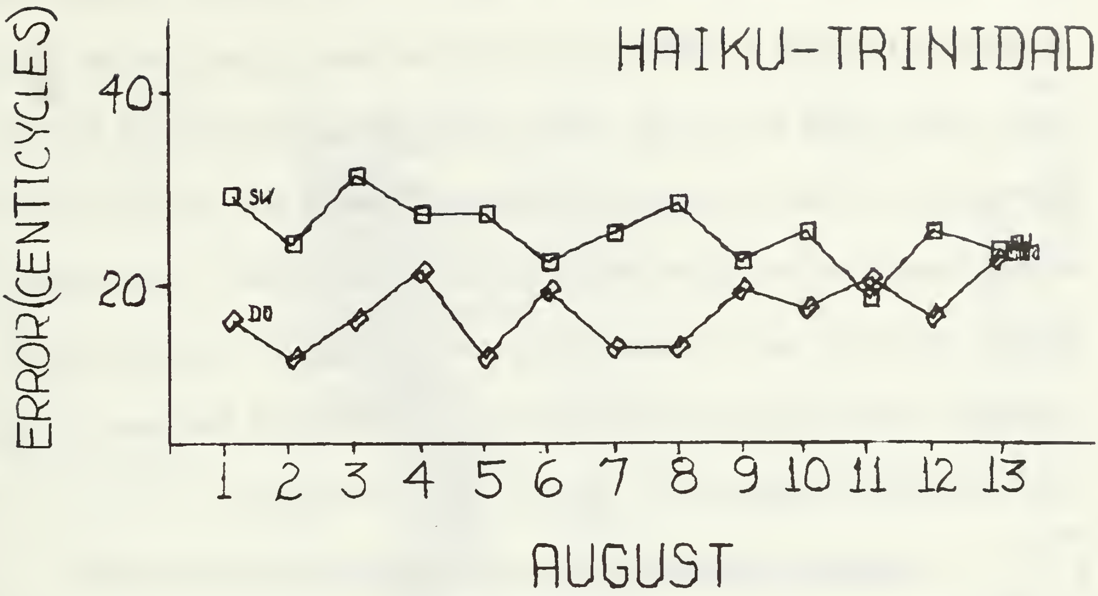


FIGURE 15



COMPARISON DIF OMEGA VS SKYWAVE

CORR. MAXIMUM ERROR 13.6 KHZ

SITE PIGEON POINT

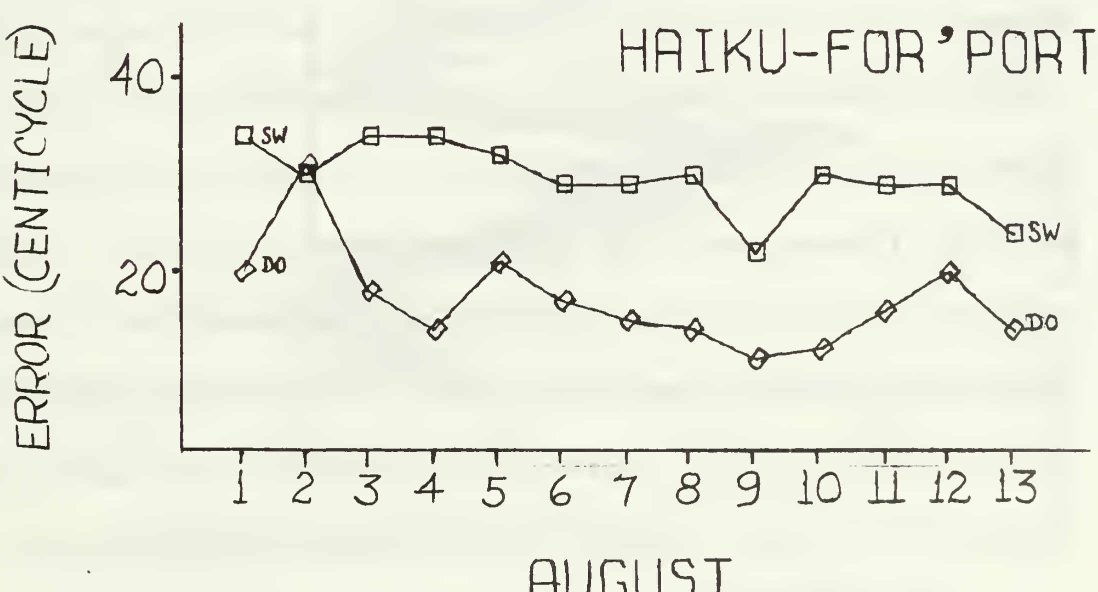


FIGURE 16

Figure 16 is a comparison of the maximum LOP errors noted when either Differential Omega or SWC ordinary Omega was utilized for the period 1-13 August 1969 at site R_1. This parameter is important as a navigation system can not be any more accurate than during the "worst case" situation, that being when the maximum LOP error exists. It is evident from Figure 16 that in most cases during this time period the differential concept reduced the maximum LOP error. Additional maximum error graphs are enclosed as Figures 63, 66, 69, 72 of Appendix A.

2. Graphical Presentation of Composite LOP Error Results

Figure 17 is a graph of the SWC ordinary Omega LOP error observed during a seven day period (7-13 August 1969) plotted as a function of time. The counterpart to this graph is Figure 18 which utilizes Differential Omega LOP errors. By comparing the density of plotted lines near the abscissa in Figures 17 and 18 it is evident that Differential Omega reduces the LOP error when compared to SWC ordinary Omega. This is especially true during the period 0600 to 1400 GMT when the SWC ordinary Omega LOP errors are relatively large and fairly random in nature. Whereas Differential Omega LOP error for the same period were only slightly greater than normal. Figures 27 to 60 contained in Appendix A are further illustrations of this type of graphical presentation. A composite of the results (average absolute LOP error) of Differential Omega versus SWC ordinary Omega compiled for the entire observation period are shown in Figures 19-22. These figures are graphs of the average absolute LOP error sampled at hourly intervals for the entire observation

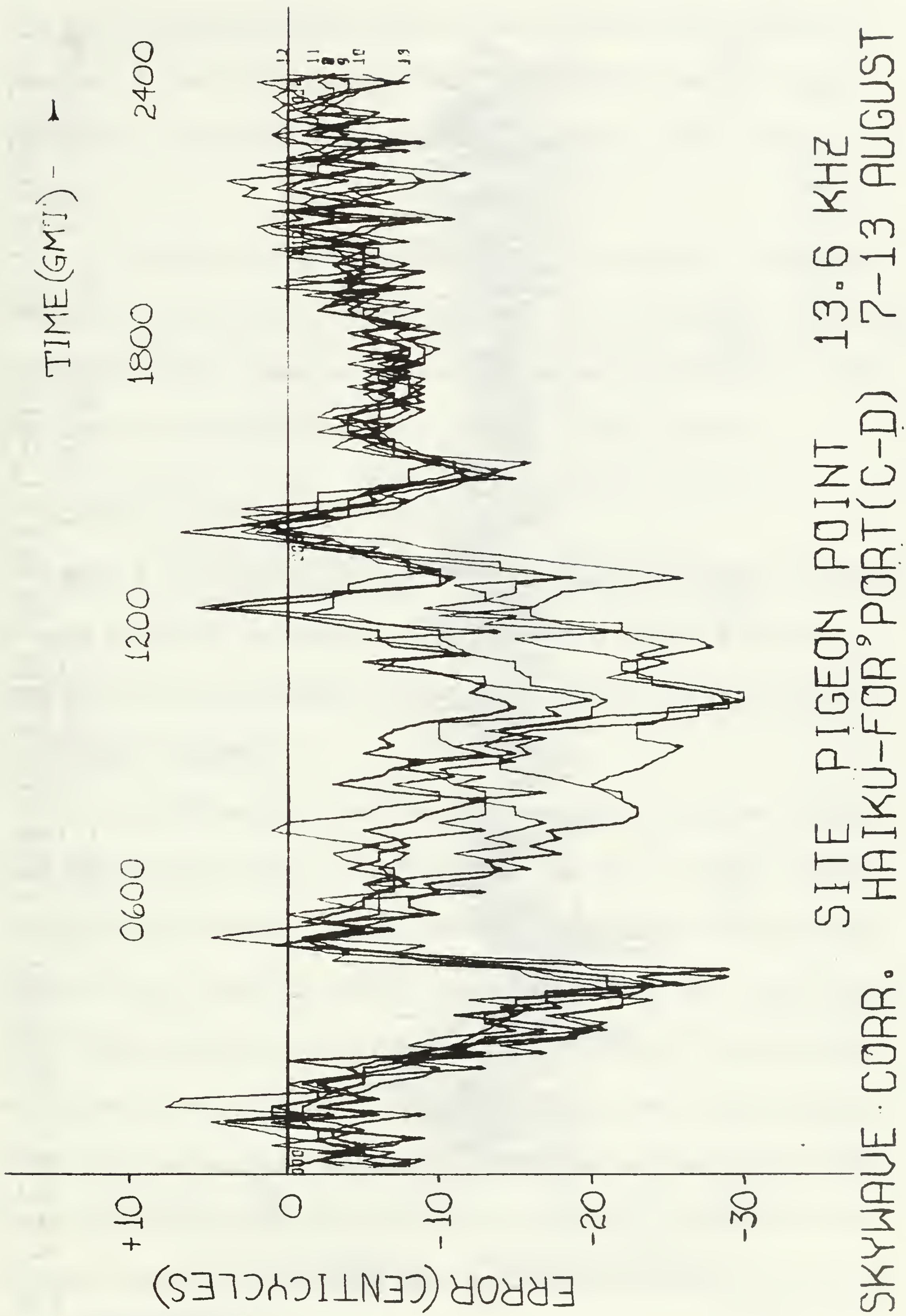
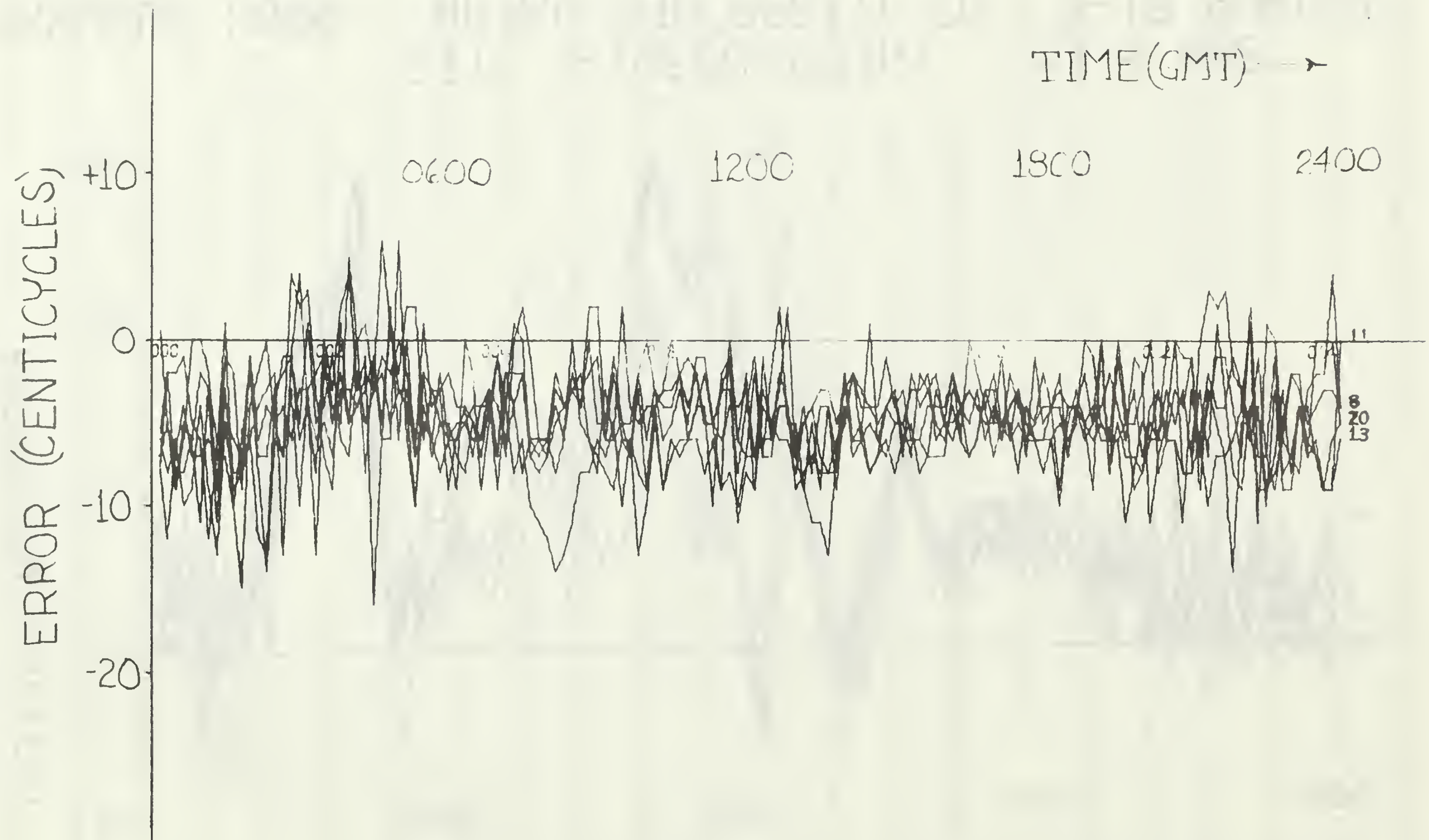

TIME (GMT) →
0600
1200
1800
2400
+10
0
-10
-20
-30
ERROR (CENTICYCLES)
SITE PIGEON POINT 13.6 KHZ
SKYWAVE CORR. HAIKU-FOR'PORT(C-D) 7-13 AUGUST

FIGURE 17



SITES USNPGS & PIGEON PT 13.6KHZ
DIFFER. OMEGA HAIKU-FOR'PORT(C-D) 7-13 AUGUST

FIGURE 18

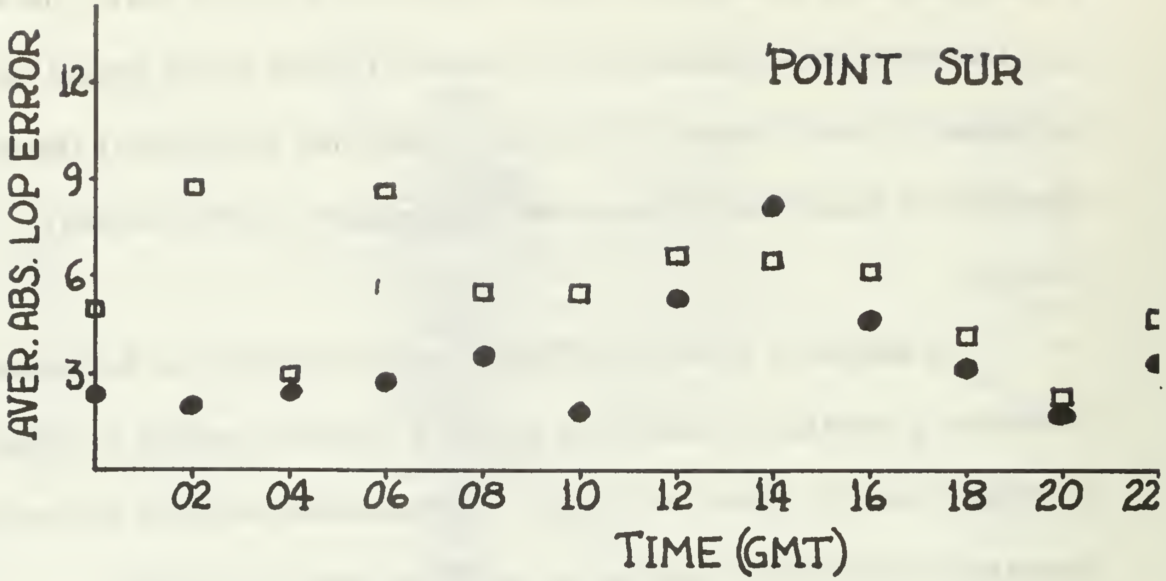
period plotted as a function of time. (It should be noted that if the sign of a LOP error for a specific time is desired Figures 27-60 should be consulted.) From Figures 19-22 it is obvious that Differential Omega does offer a significant improvement as compared to SWC ordinary Omega.

A method of examining the relative improvement of Differential Omega as a function of separation distance and time periods is illustrated by Figures 23-26. These are graphs of the average absolute LOP errors compiled for the entire observation period for sites R_1 and R_2 .

F. CONCLUSIONS

Table 4 is a tabular summary of the averaged parameters observed at sites R_1 and R_2 for the entire testing period. From Table 4 values, Figures 14-26 and the graphs contained in Appendix A the following conclusions are drawn:

1. The Differential Omega concept improves the system accuracy over SWC ordinary Omega by reducing the LOP error in approximately 90% of the observations. The actual overall improvement factor for an average 24 hour period is slightly greater than two to one. The greatest improvement factor was experienced during the periods of local sunrise and sunset (refer to Figures 19-22). The improvement factor during the local sunset period (0400 GMT) was on the order of five to one. This large improvement does not imply that the Differential Omega LOP error at these times was appreciably smaller than for other times but that the SWC ordinary Omega LOP error was much greater than normal. Another



AVERAGE ABSOLUTE LOP ERROR

SWC ORDINARY OMEGA

DIFFERENTIAL OMEGA

TRINIDAD - HAIKU 10.2 KHZ

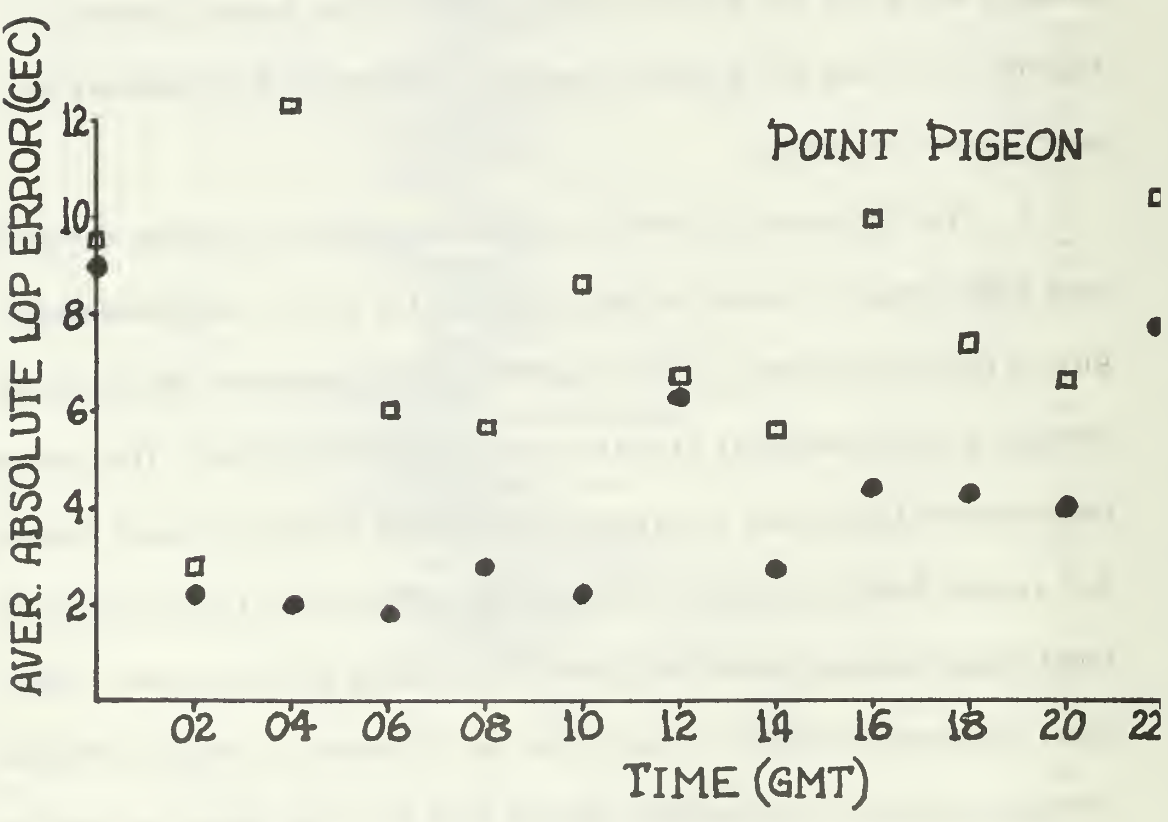
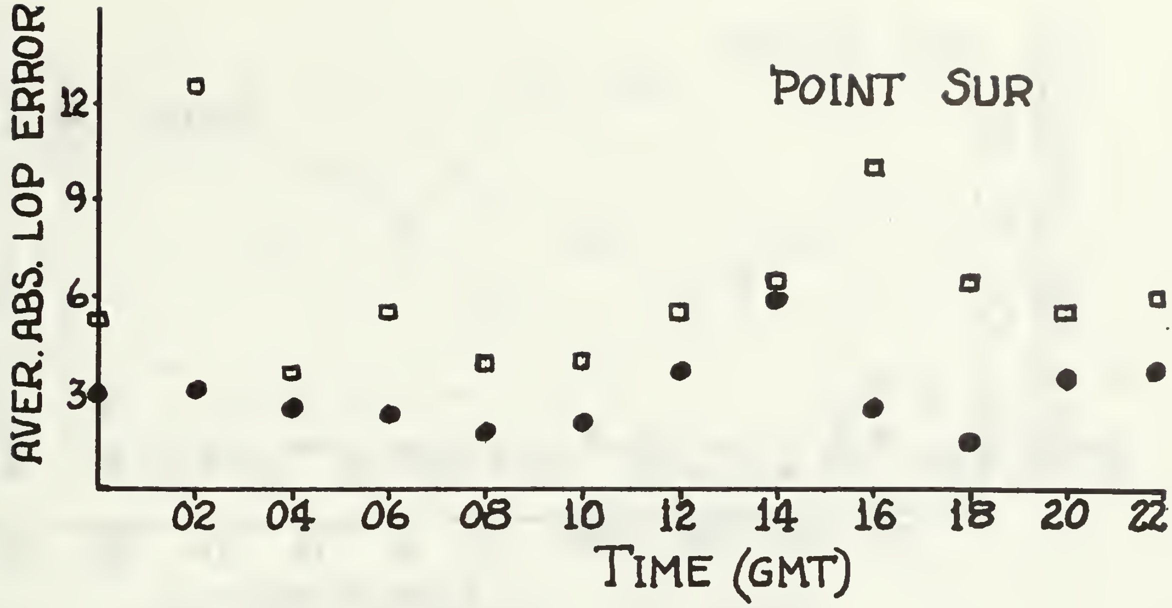


FIGURE 19



AVERAGE ABSOLUTE LOP ERROR
SWC ORDINARY OMEGA
DIFFERENTIAL OMEGA
HAIKU - FORRESTPORT 10.2 KHZ

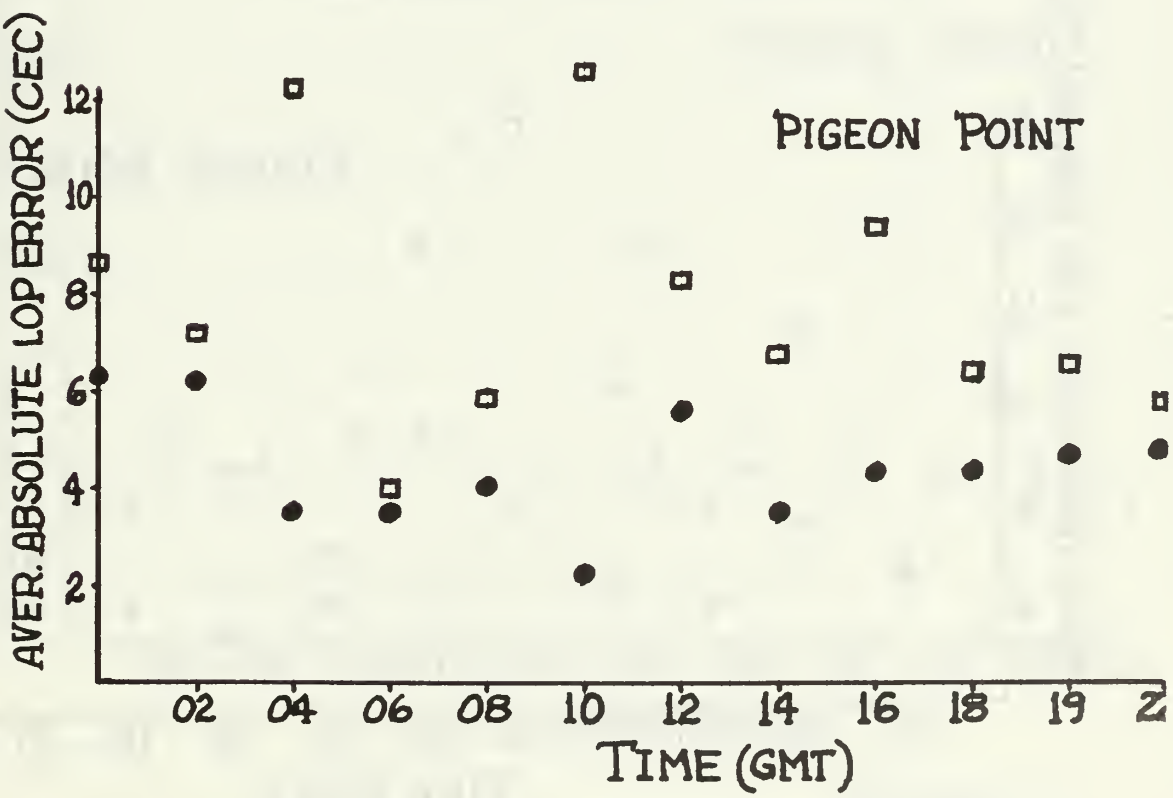
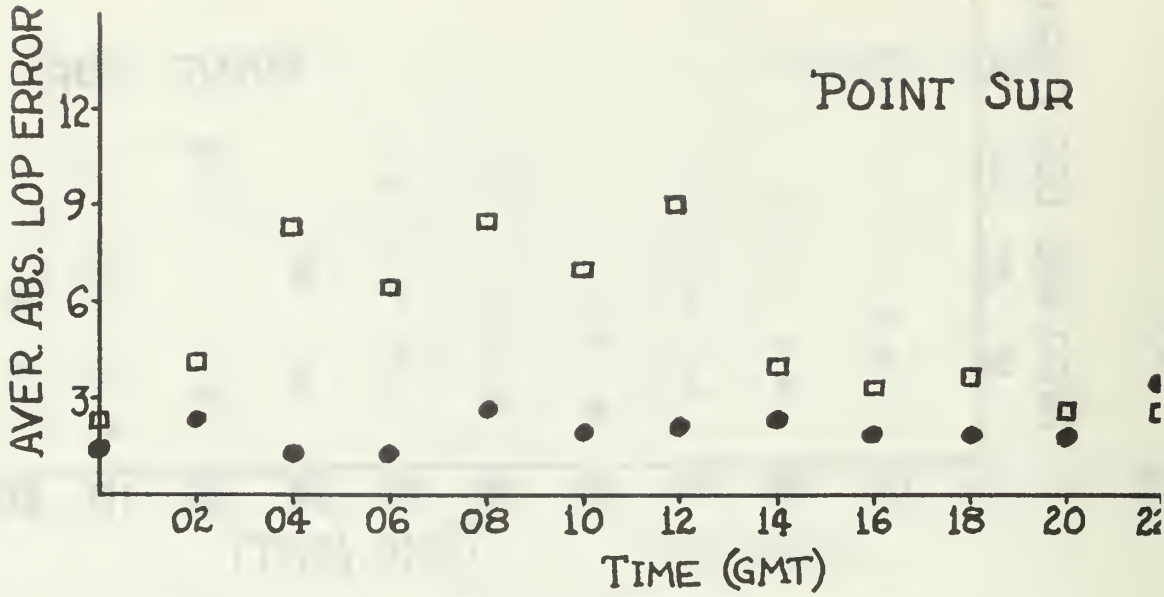


FIGURE 20



AVERAGE ABSOLUTE LOP ERROR
-□-□- SWC ORDINARY OMEGA
-●-●- DIFFERENTIAL OMEGA
TRINIDAD - HAIKU 13.6 KHZ

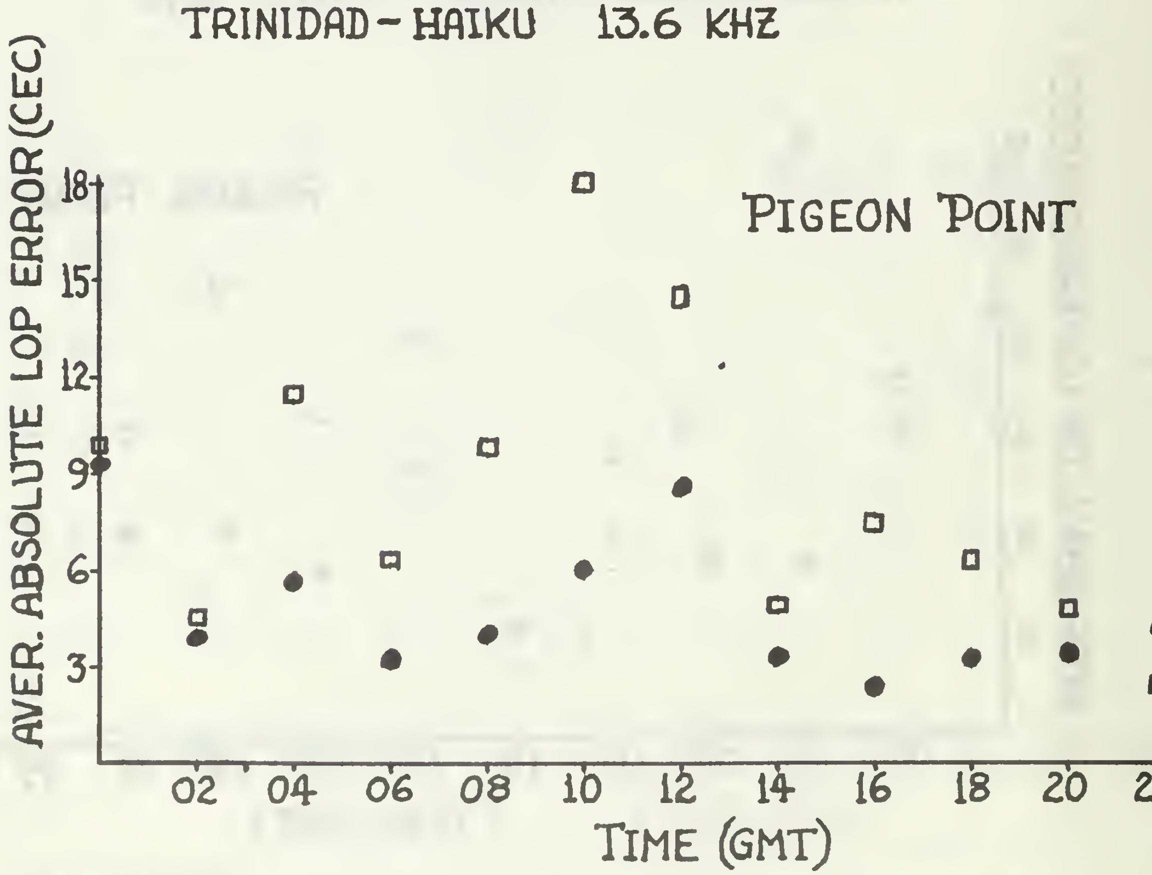
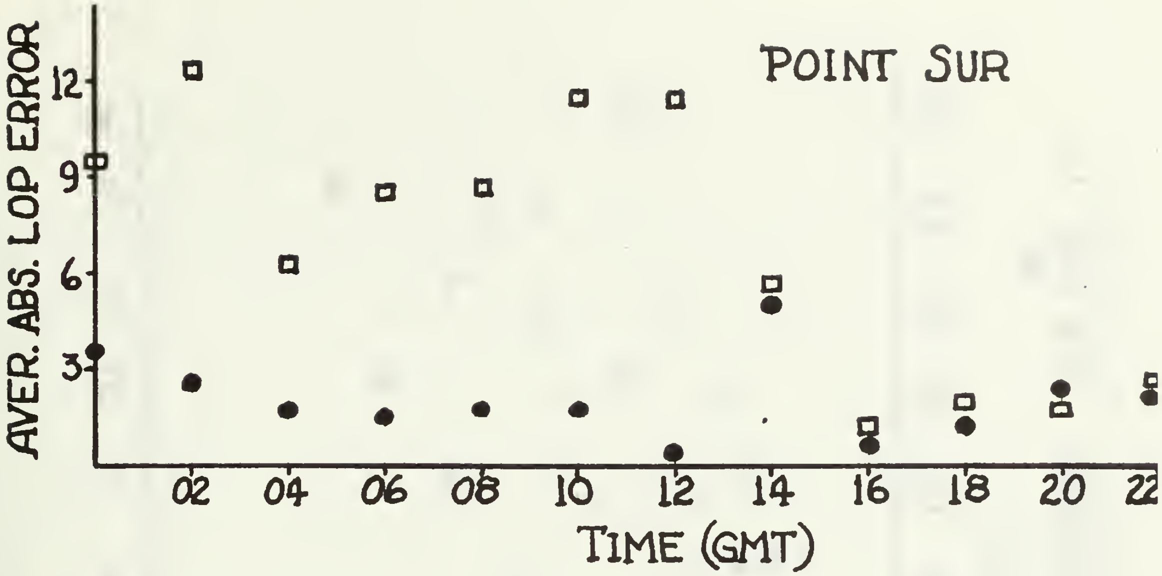


FIGURE 21



AVERAGE ABSOLUTE LOP ERROR
-□-□- SWC ORDINARY OMEGA
-●-●- DIFFERENTIAL OMEGA
HAIKU - FORRESTPORT 13.6 KHZ

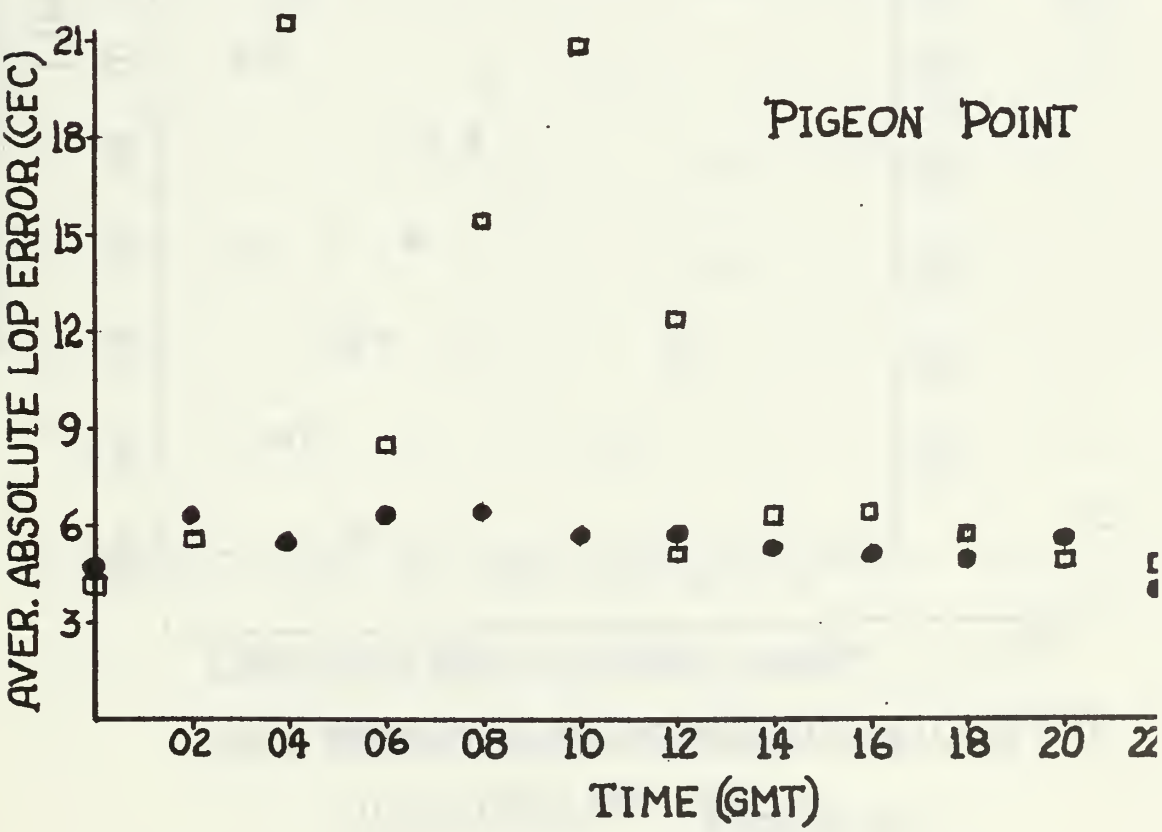


FIGURE 22

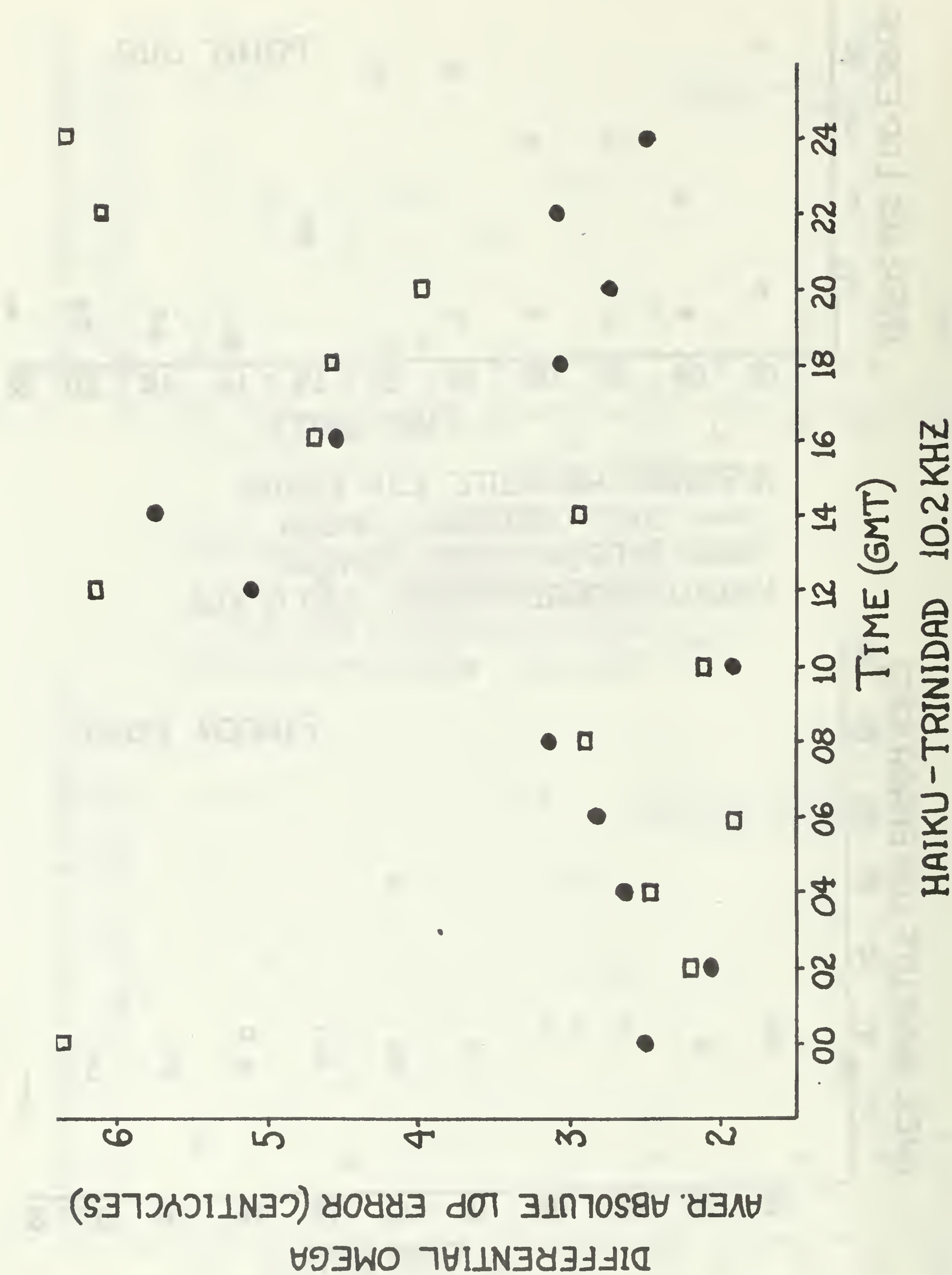
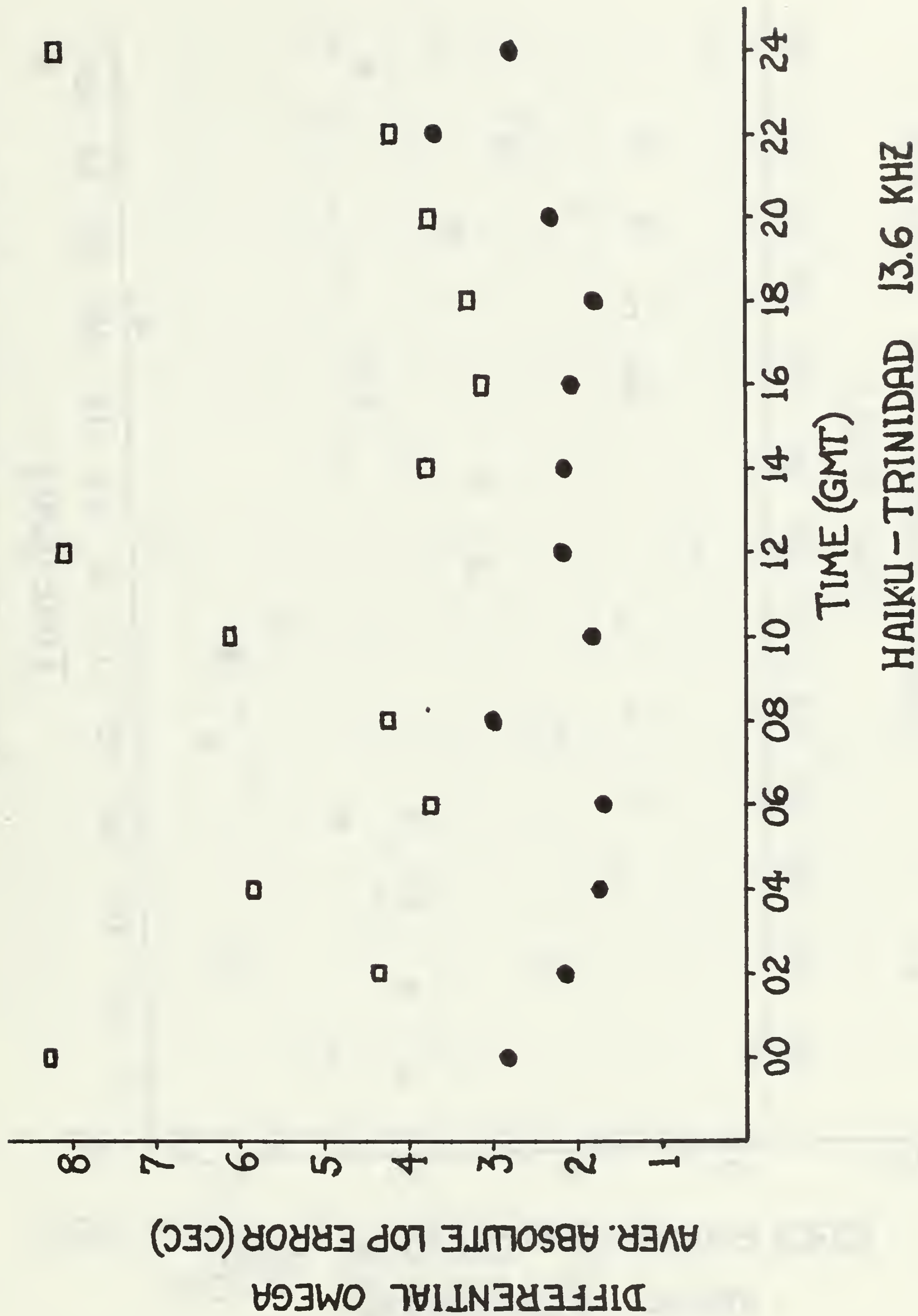

DIFFERENTIAL OMEGA
AVER. ABSOLUTE LOP ERROR (CENTICYCLES)
2
3
4
5
6
00
02
04
06
08
10
12
14
16
18
20
22
24
TIME (GMT)
HAIKU-TRINIDAD 10.2 KHZ

FIGURE 23



DIFFERENTIAL OMEGA
AVER. ABSOLUTE LOP ERROR (CEC)
8
7
6
5
4
3
2
1
00
02
04
06
08
10
12
14
16
18
20
22
24
TIME (GMT)
HAIKU-TRINIDAD 13.6 KHZ

FIGURE 24

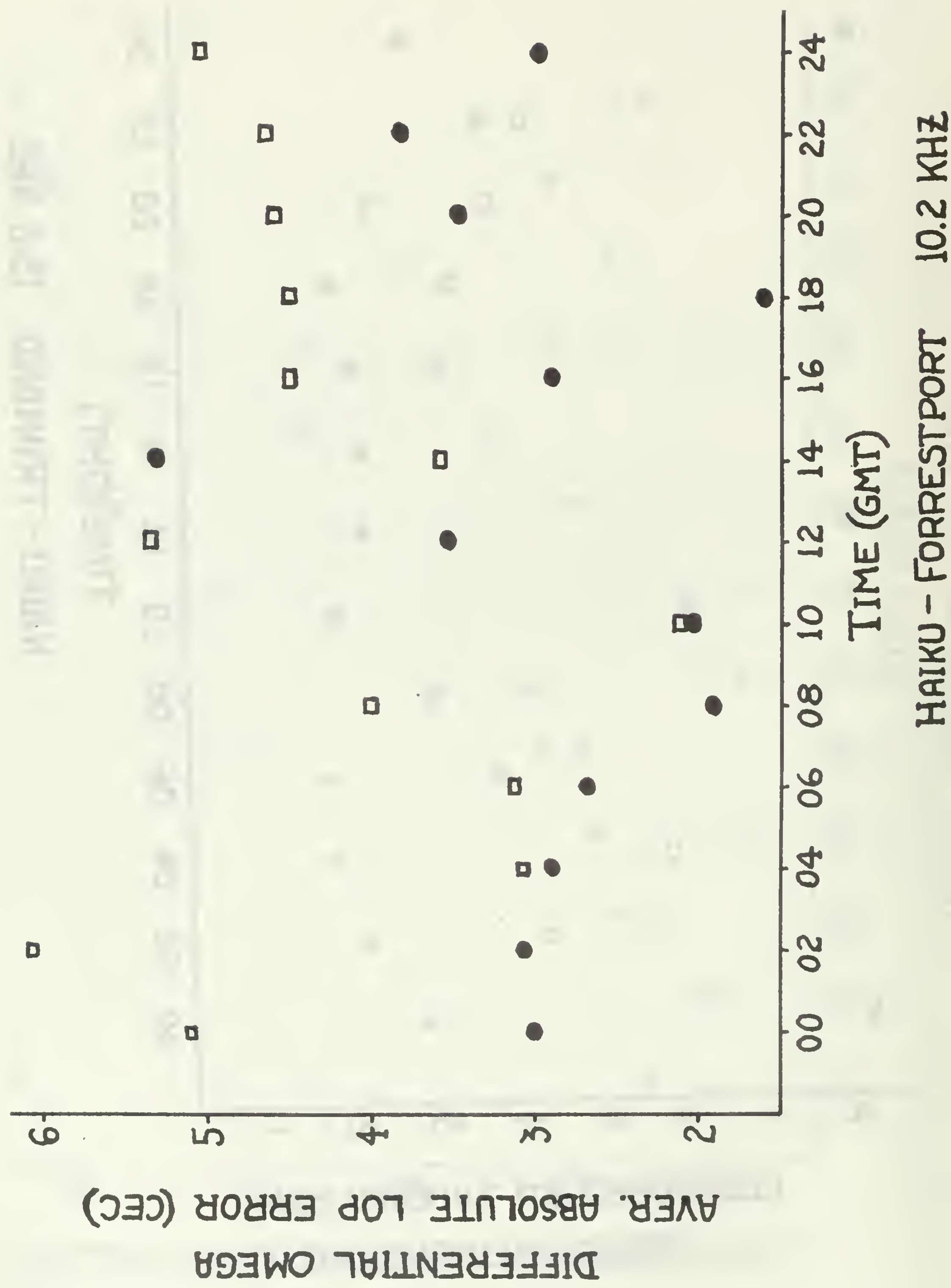

HAIKU - FORRESTPORT 10.2 KHZ
TIME (GMT)
00 02 04 06 08 10 12 14 16 18 20 22 24
DIFFERENTIAL OMEGA
AVER. ABSOLUTE LOP ERROR (CEC)
2 3 4 5 6

FIGURE 25

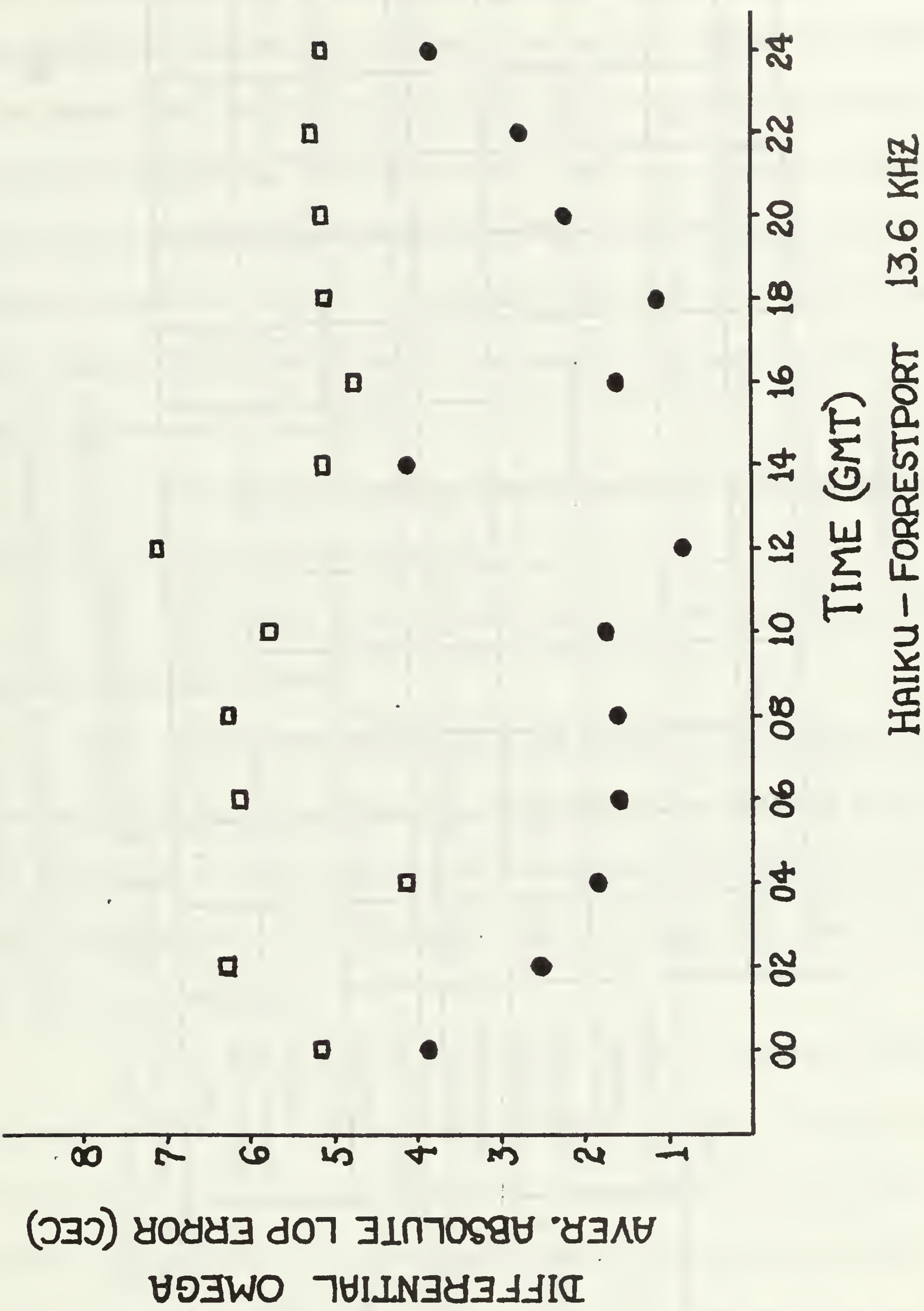

DIFFERENTIAL OMEGA
AVER. ABSOLUTE LOP ERROR (CEC)
1
2
3
4
5
6
7
8
00
02
04
06
08
10
12
14
16
18
20
22
24
TIME (GMT)
HAIKU - FORRESTPORT 13.6 KHZ

FIGURE 26

		Parameters											
		Average LOP Error				Standard Deviation				Maximum Error			
		10.2 kHz		13.6 kHz		10.2 kHz		13.6 kHz		10.2 kHz		13.6 kHz	
Site	Mode	BC	CD	BC	CD	BC	CD	BC	CD	BC	CD	BC	CD
USCG Light Station, Pigeon Point, California R_1	SWC Ordindary Omega	7.95	8.54	8.53	10.05	5.74	4.89	6.17	7.25	32.6	23.0	27.0	30.3
	Differential Omega	4.95	5.02	4.61	5.56	4.20	3.05	3.81	3.38	21.0	15.1	20.5	18.4
	Improvement Factor	1.61	1.70	1.85	1.81	1.37	1.60	1.62	2.14	1.55	1.52	1.32	1.65
USCG Light Station, Point Sur, California R_2	SWC Ordinary Omega	5.72	7.02	5.73	6.93	4.07	4.21	4.43	5.00	18.4	20.7	20.4	19.7
	Differential Omega	3.79	3.28	2.85	2.12	3.02	2.34	2.06	1.30	13.7	12.9	11.1	7.6
	Improvement Factor	1.54	2.14	2.01	3.27	1.38	1.81	2.15	3.85	1.35	1.63	1.84	2.59

Note: (1) All values are in centicycles (cec)

(2) $\text{Improvement Factor} = \dfrac{\text{value for SWC ordinary Omega}}{\text{Corresponding value for Differential Omega}}$

TABULAR SUMMARY OF OBSERVED PARAMETERS

TABLE 4

large improvement of approximately four to one occurred during the sunrise period (1000 GMT) at Forrestport. The nighttime (0400-1200 GMT) improvement factor was fairly steady and ranged between two and three to one. Late afternoon (2200-0200 GMT) conditions provided the least improvement of Differential Omega over SWC ordinary Omega with a resulting improvement factor of approximately 1.3 to one. Not only were these afternoon Differential Omega observations relatively inaccurate but they were also highly unstable.

2. The standard deviation was reduced by a factor of 50% by the utilization of the differential concept.

3. Differential Omega reduced the daily maximum Omega LOP error by approximately 40%.

4. Although the small size of the sample space (two user sites) does leave this conclusion open for argument, it appears from Table 4 and Figures 23-26 that a reduction in the separation distance result in a substantial increase in the Differential Omega improvement factor for all the parameters observed.

5. The differential concept improved both the Omega system accuracy and reliability during the occurrences of SID's. Several SID's occurred during the testing period which demonstrated the improvement possible through the use of Differential Omega. But the most graphic example occurred during 30 September - 2 October 1969 when several SID's and associated propagation anomalies took place. Table 5 is a summary of the important parameters observed for that period and

Parameters (cec)

Date	Average LOP Error		Standard Deviation		Maximum Error		
	SWC	DO	SWC	DO	SWC	DO	
27	3.96	1.73	2.81	0.86	13	5	Normal Conditions
28	5.32	2.54	3.52	1.33	18	7	
29	7.55	2.35	6.97	1.40	25	13	Abnormal Conditions
30	14.26	2.38	10.20	1.35	39	7	
1	9.34	2.70	6.16	1.88	20	9	
2	9.70	1.98	6.14	1.24	24	7	
3	4.01	2.23	3.10	1.21	15	6	Normal Conditions

Site: USCG Light Station, Point Sur, California

Date: 27 Sept. - 3 Oct. 1969

Freq: 13.6 kHz

LOP Pair: Haiku-Forrestport

DO: Differential Omega

SWC: SWC Ordinary Omega

"IMPROVEMENT DUE TO DIFFERENTIAL OMEGA DURING ABNORMAL CONDITIONS"

TABLE 5

demonstrates the improvement realized through the utilization of Differential Omega. Parameter values for 27-28 September and 3 October 1969 are also listed to be used as a reference norm.

6. Due to the limited number of observation sites no definite conclusions could be reached regarding the Differential Omega improvement factor as a function of the relative bearing between the monitor and user.

G. ERRORS

The following are the major sources of error noted during this evaluation study:

1. A major source of error in the results of the SWC ordinary Omega LOP's are the skywave corrections values (refer Figures 17, 29, 31, 33, 35, 41 and 45). It is apparent that even though the LOP error of the SWC ordinary Omega results are large they are at least in most instances very predictable. By utilizing the repeatability of the LOP errors it would possible to derive new skywave corrections which would provide a definite improvement in the SWC ordinary results.

2. Another error in this evaluation study was the offset error which was present in both the SWC ordinary and Differential Omega Pigeon Point C-D average LOP error results. A negative bias error of approximately five cec was present in all site R_1's C-D average LOP error graphs (Figures 29-32, 35-36, 39-40, 43-46). This was the case regardless of which Omega frequency was being evaluated. The cause of this

error has not been determined. A possible explanation might be that either the position of Pigeon Point's Omega antenna was incorrect or the antenna's position was correct and the true value of the C-D LOP used for this position was in error. Two other factors which add confusion to the situation are the absence of any biasing in the average LOP error results for Pigeon Point B-C and Point Sur C-D. This lack of biasing indicates that both the Pigeon Point position and the USNPGS C-D value were correct and therefore the true value of Pigeon Point C-D LOP was in error. This LOP value was rechecked and verified correct by NELC.

3. Manual interpretation and handling of the data might be the cause for isolated cases of error in the Omega LOP's. But definitely not to the extent to offer any explanation for the biasing problem mentioned above. In an attempt to remove the human data handling errors all digital data (strip chart sample values, digital data on computer cards, etc.) was double checked by an individual other than the compiler.

4. Slight errors might be caused by the inability of the analog recorders to be perfectly time synchronized. As stated before, continuous watchstanding prevented the time deviation between recorders to be greater than five minutes. It is believed the effect on the Differential Omega results due to this small time discrepancy is negligible.

VI. SUMMARY

From research and the results of the Differential Omega evaluation test conducted in connection with this thesis, the following conclusions are drawn:

1. The Omega Navigation System will provide a worldwide, relatively accurate, inexpensive all weather navigation system.

2. Differential Omega offers a definite improvement in accuracy and reliability over SWC ordinary Omega for small separation distances. A conservative estimate of the improvement factor is two to one.

3. The results of the feasibility test conducted indicate an average Differential Omega LOP error for 10.2 kHz in the Monterey Bay vicinity of 4.98 cec (0.4 nm) for a separation distance of 40.2 nm and 3.53 cec (0.28 nm) at separation distance of 17.7 nm. It is reasonable to assume that the differential concept would at least perform as well for the New York Harbor region. This would result in a maximum position fix (with two LOPs at a crossing angle of 30 degrees) error of 1.5 nm in the New York Differential Omega region. This is not the ultimate degree of accuracy desired but still is sufficient to be utilized in a harbor sea lane plan.

4. Coast Guard radiobeacons are the logical choice to serve as the Differential Omega communications link.

5. Carrier separation modulation is an accurate, rapid and inexpensive method of transmitting the Differential Omega correction information. The method of incorporating carrier separation modulation

illustrated in Figure 10 permits the largest degree of flexibility and may be adapted to any dual carrier radiobeacon transmitter.

6. The Differential Omega correction terms should be transmitted as a difference value in cec in lieu of a Δ Latitude Δ Longitude correction.

APPENDIX A - GRAPHICAL RESULTS OF FEASIBILITY TEST

The graphs and figures contained in this Appendix are the results of the feasibility test as described in Section V. Figures 27 to 60 have been set up on alternate pages to permit comparison to be made between SWC ordinary Omega and Differential Omega results. The selected parameters which are compared in Figures 61 - 72 are average LOP error, standard deviation and maximum LOP error.

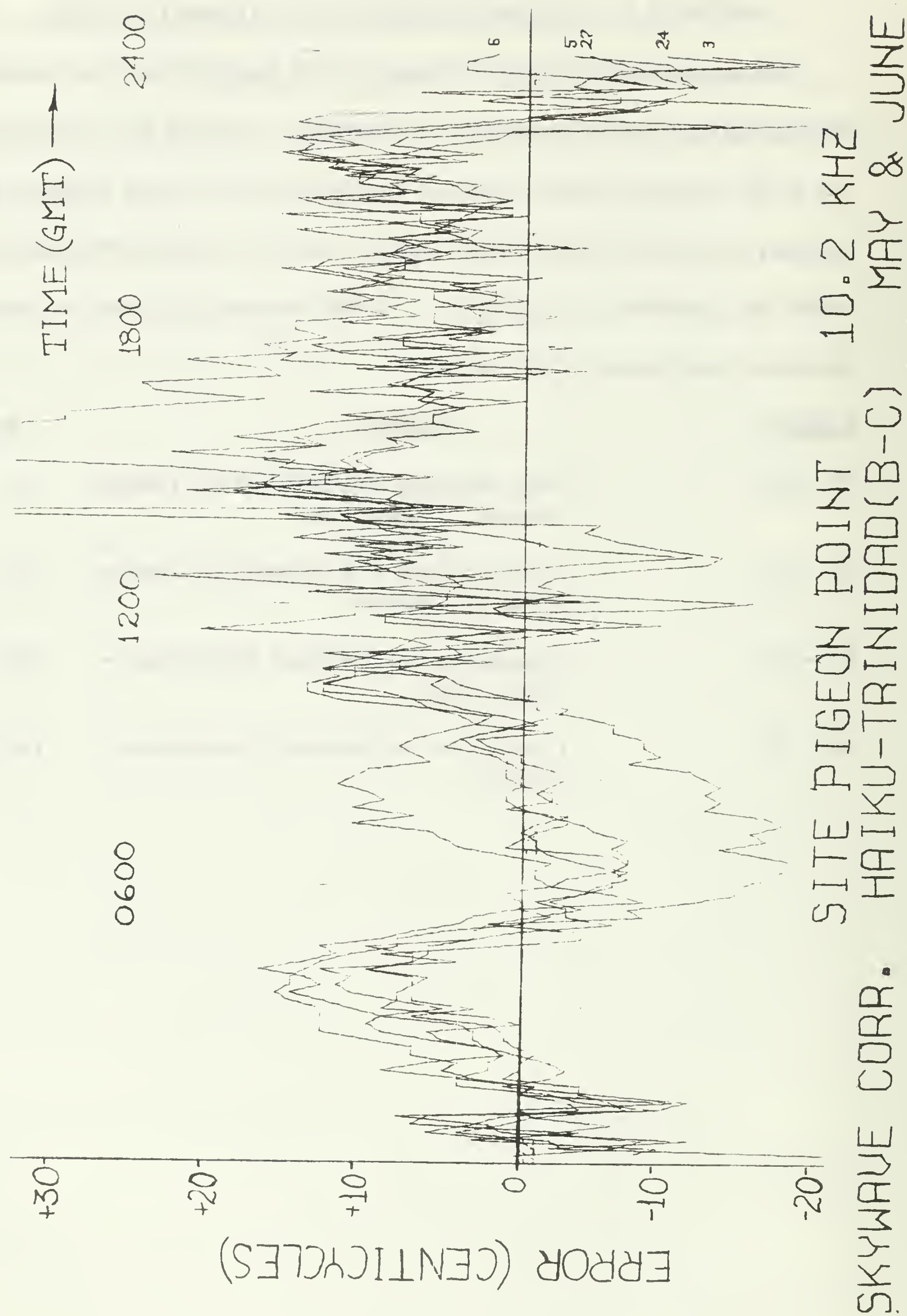

SKYWAVE CORR. HAIKU-TRINIDAD(B-C) MAY & JUNE
SITE PIGEON POINT 10.2 KHZ
ERROR (CENTICYCLES)
+30
+20
+10
0
-10
-20
TIME (GMT) →
0600
1200
1800
2400
6
5
27
24
3

FIGURE 27

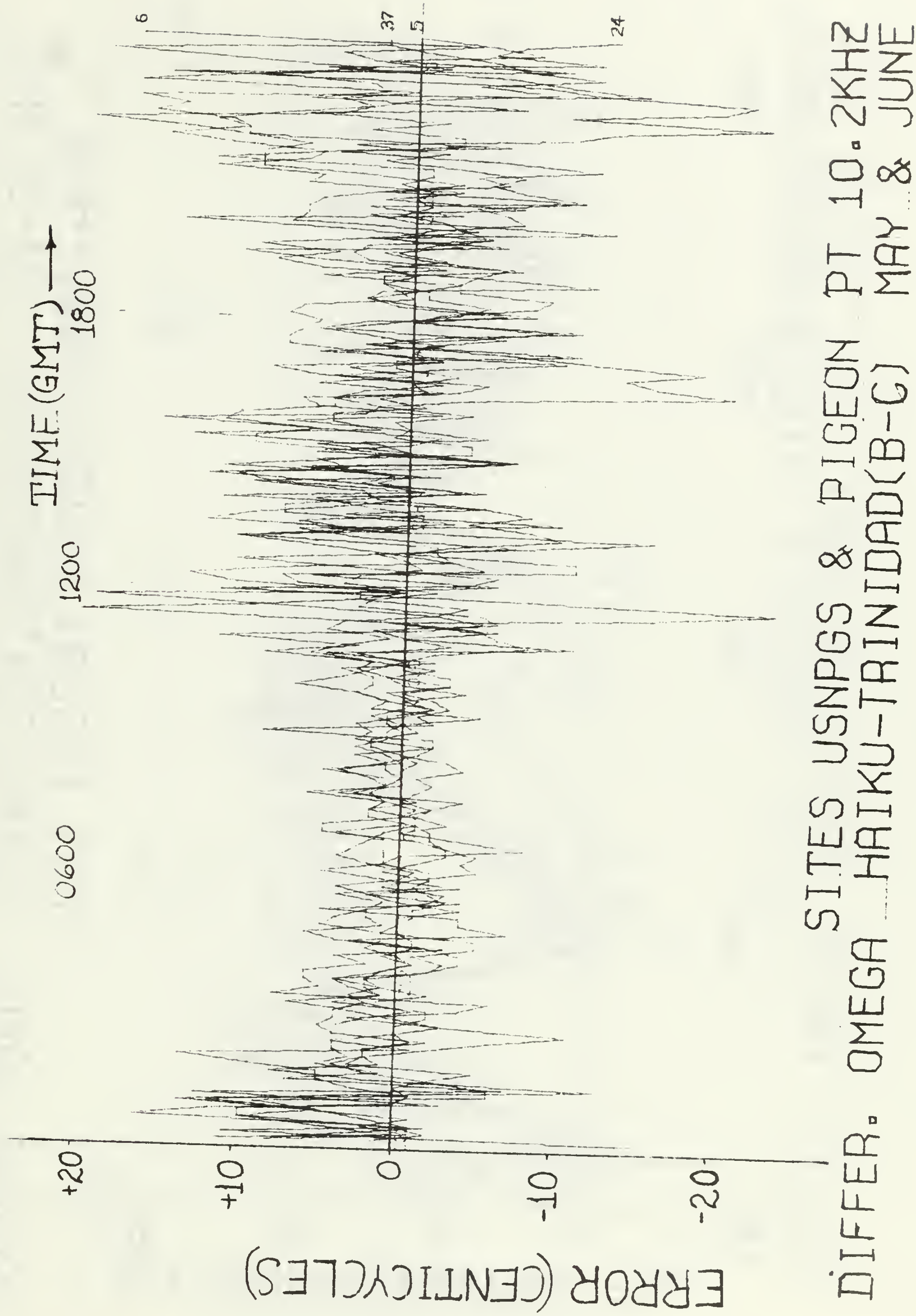
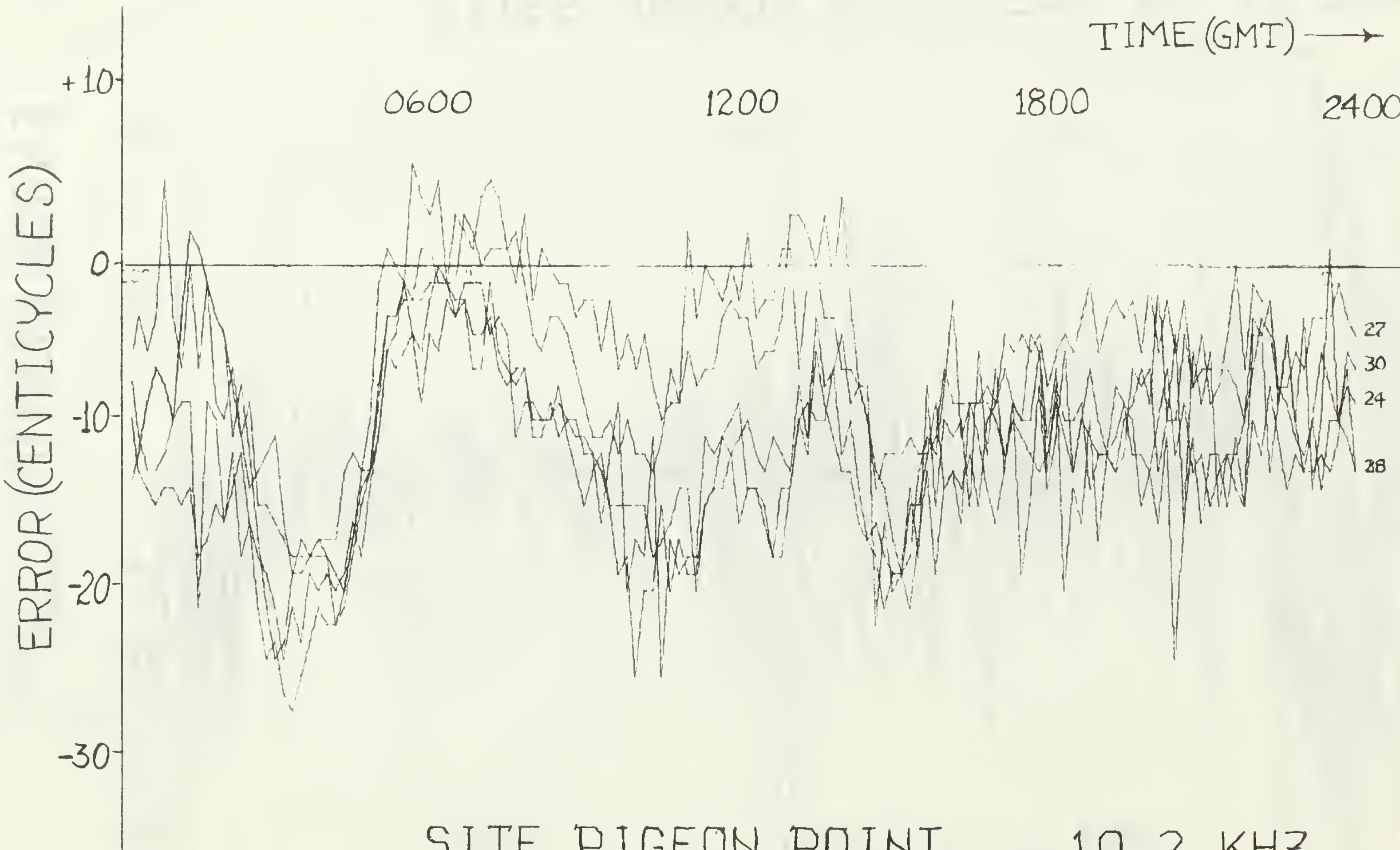

ERROR (CENTICYCLES)
+20
+10
0
-10
-20
TIME (GMT) ⟶
0600
1200
1800
6
37
5
24
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) MAY & JUNE
SITES USNPGS & PIGEON PT 10.2KHZ

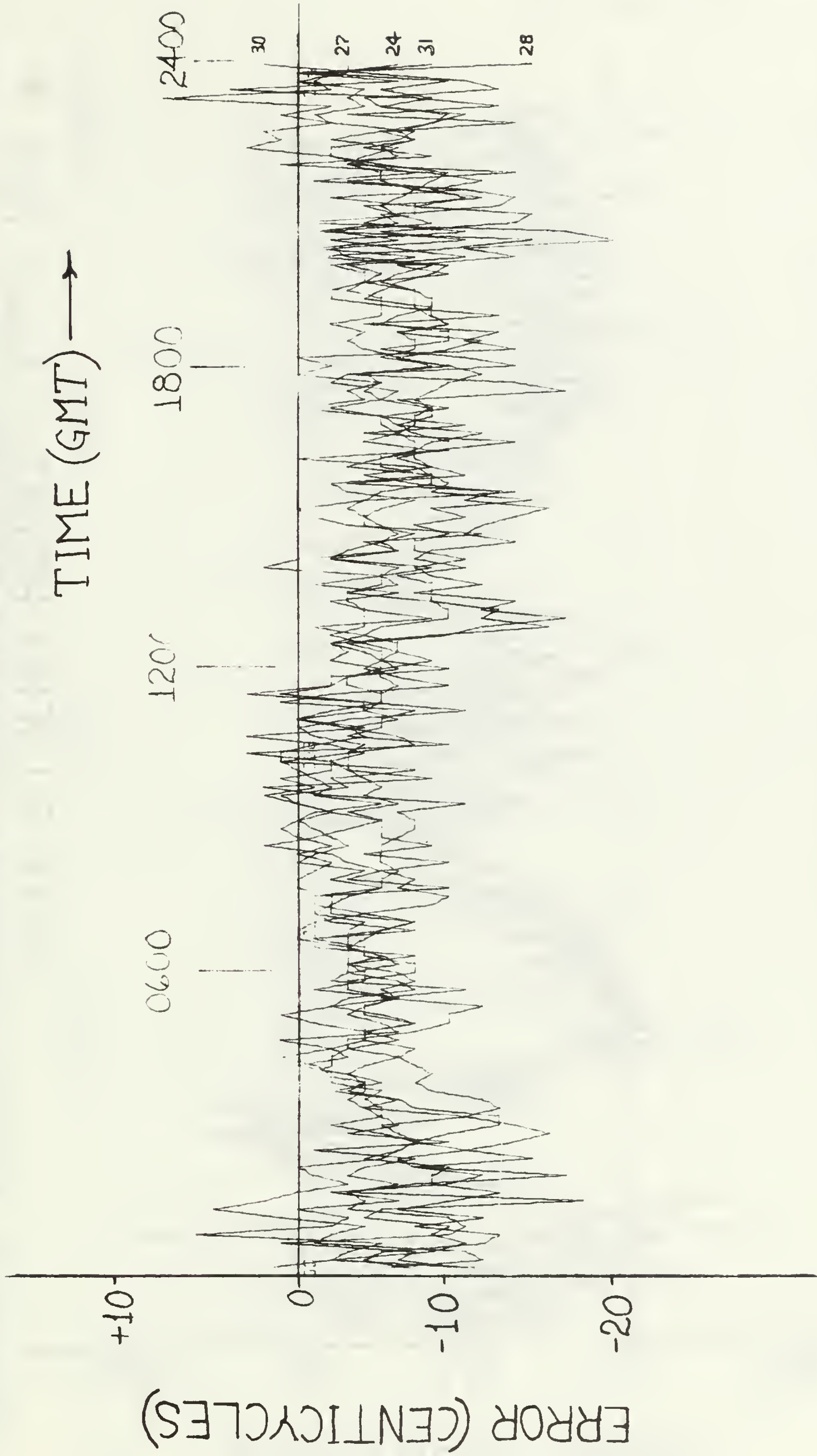
FIGURE 28



SITE PIGEON POINT 10.2 KHZ

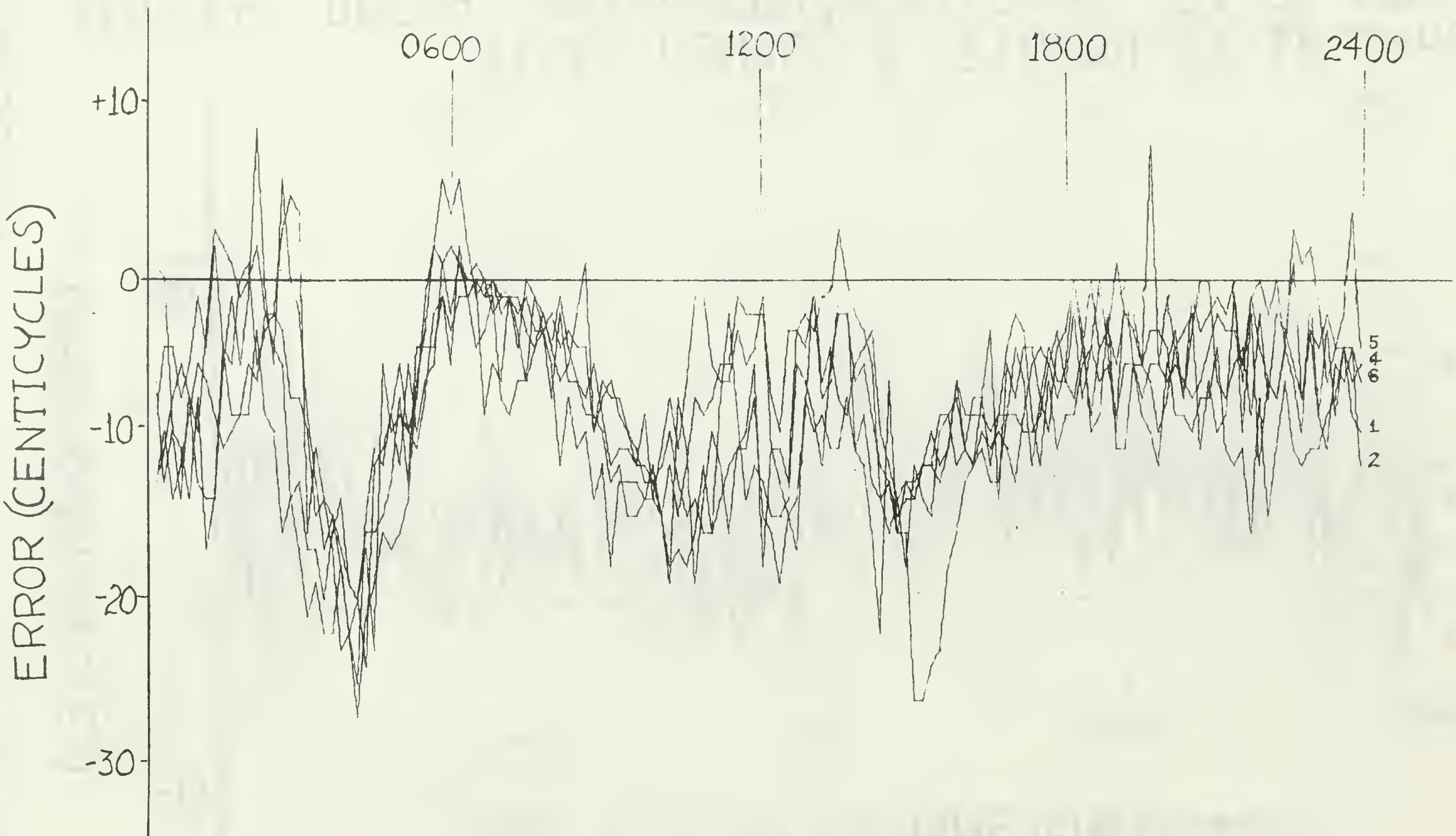
SKYWAVE CORR. HAIKU-FOR'PORT(C-D) 24-31 MAY

FIGURE 29



SITES USNPGS & PIGEON PT 10.2KHZ
DIFFER. OMEGA HAIKU-FOR'PORT(C-D) 24-31 MAY

FIGURE 30



SITE PIGEON POINT 10.2 KHZ
SKYWAVE CORR. HAIKU-FOR'PORT(C-D) 1 - 6 JUN

FIGURE 31

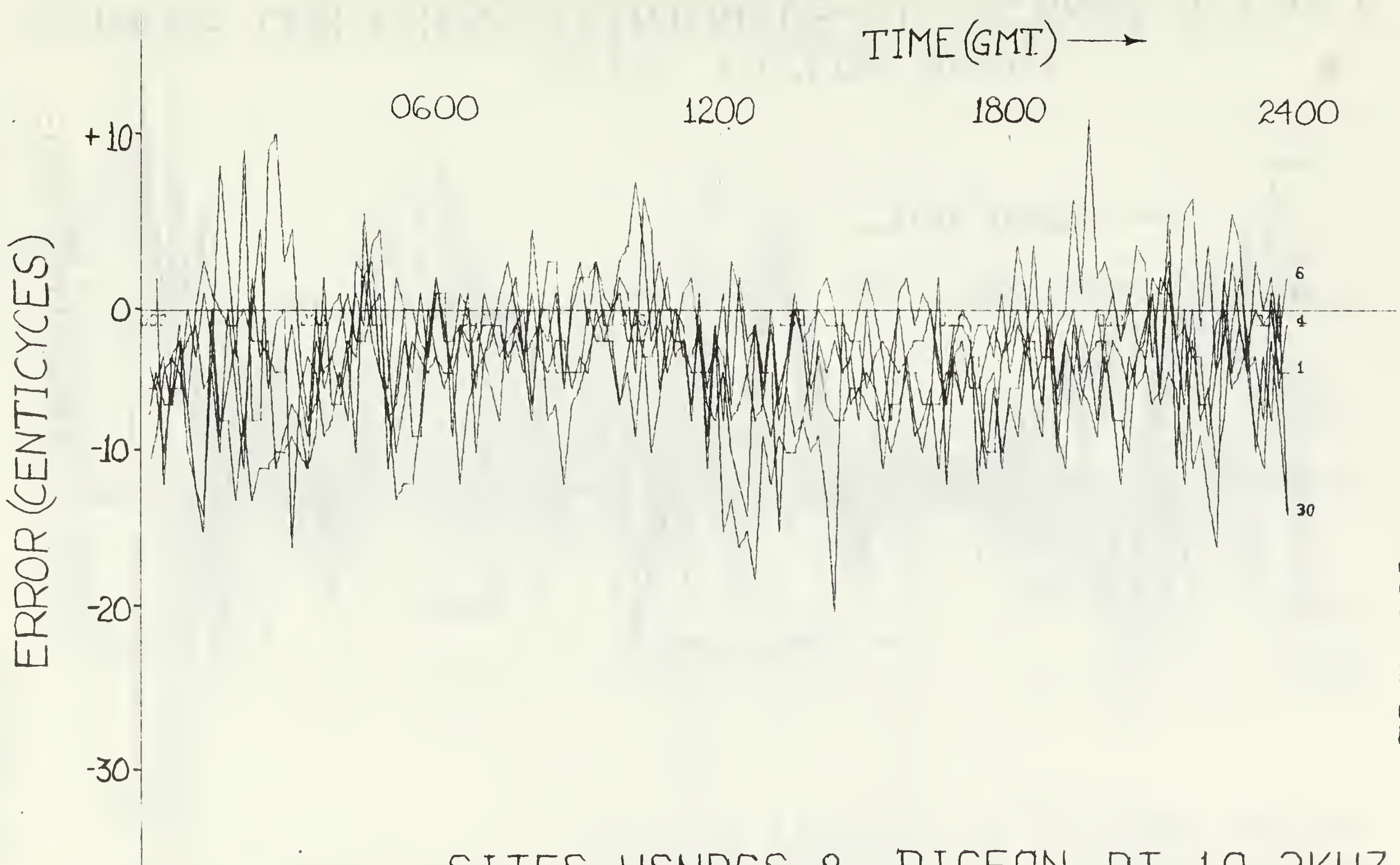
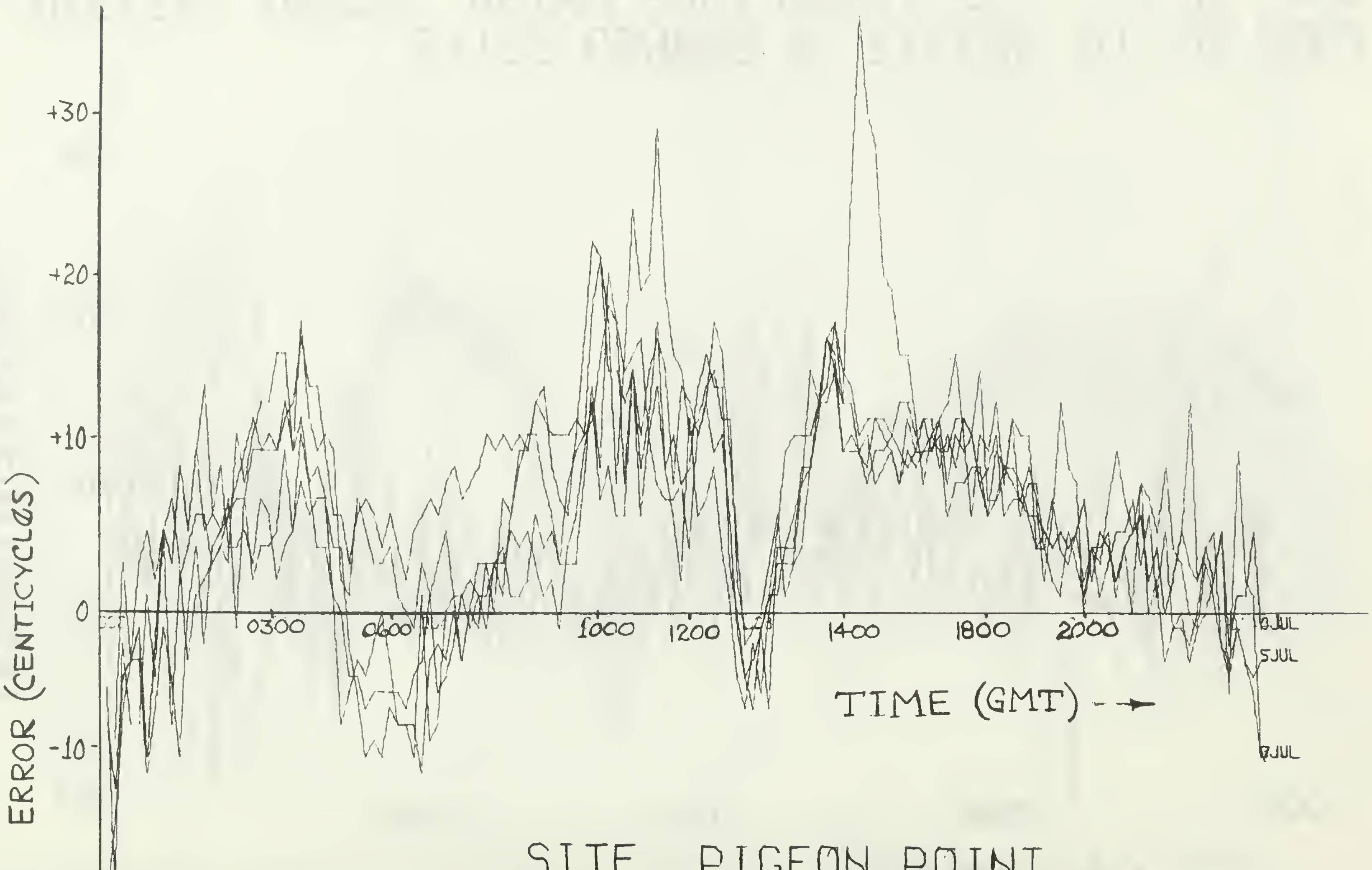


FIGURE 32

SITES USNPGS & PIGEON PT 10.2KHZ
DIFFER. OMEGA HAIKU-FOR'PORT(C-D) 1 — 6 JUNE

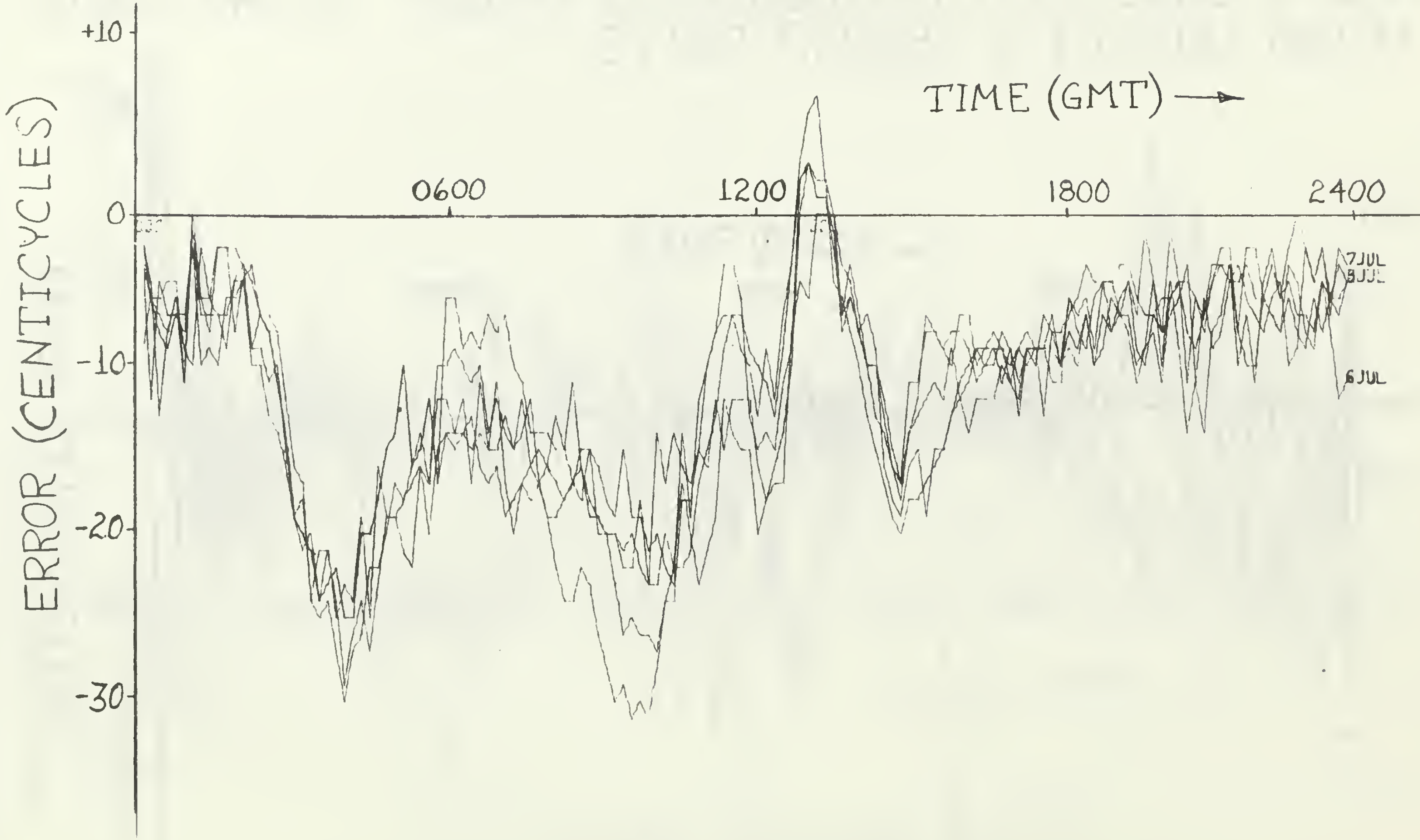


SITE PIGEON POINT
SKYWAVE COR.HAIKU-TRINIDAD(B-C) 13.6KHZ 3-7JULY

FIGURE 33

SITES USNPGS & PIGEON POINT
DIFF.OMEGA HAIKU-TRINIDAD(B-C) 13.6KHZ 3-7JUL

FIGURE 34



SITE PIGEON POINT
SKYWAVE COR. HAIKU-FOR'PORT(C-D) 13.6KHZ 3-7JUL

FIGURE 35

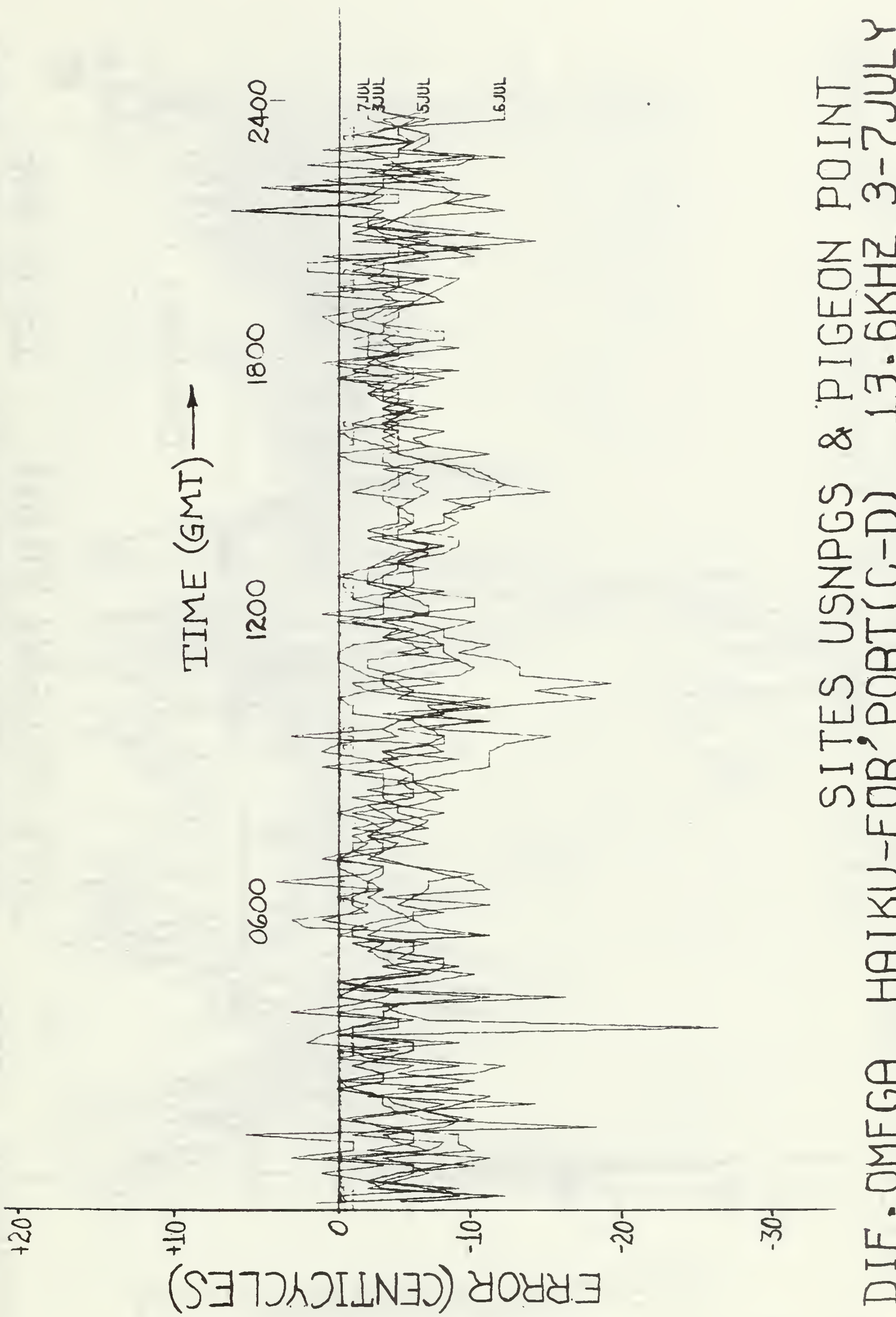

SITES USNPGS & PIGEON POINT
DIF. OMEGA HAIKU-FOR'PORT(C-D) 13.6KHZ 3-7JULY
TIME (GMT)
0600
1200
1800
2400
7JUL
3JUL
5JUL
6JUL
ERROR (CENTICYCLES)
+20
+10
0
-10
-20
-30

FIGURE 36

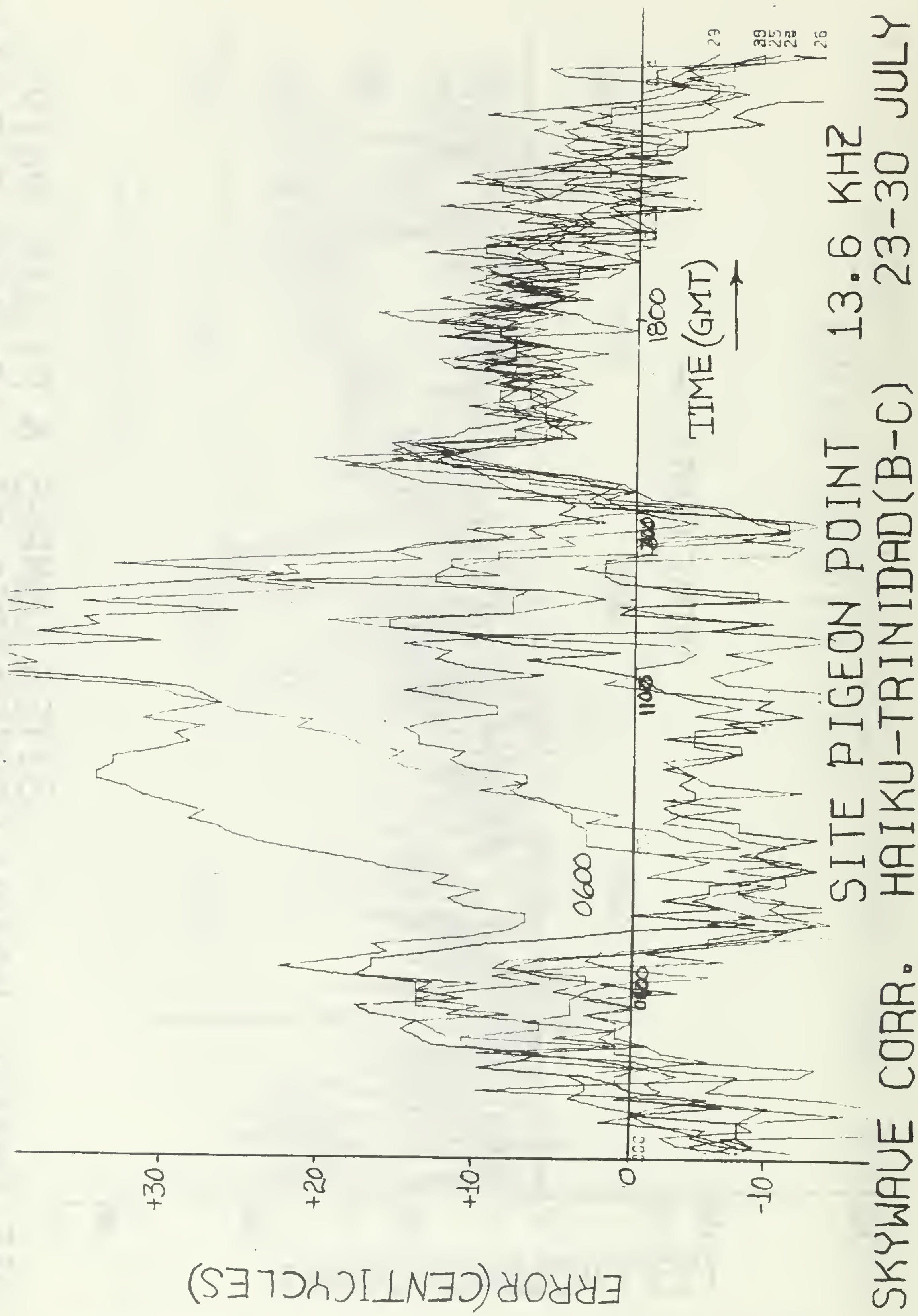

SKYWAVE CORR. SITE PIGEON POINT 13.6 KHZ
HAIKU-TRINIDAD(B-C) 23-30 JULY
ERROR(CENTICYCLES)
+30
+20
+10
0
-10
0600
1800
TIME (GMT)

FIGURE 37

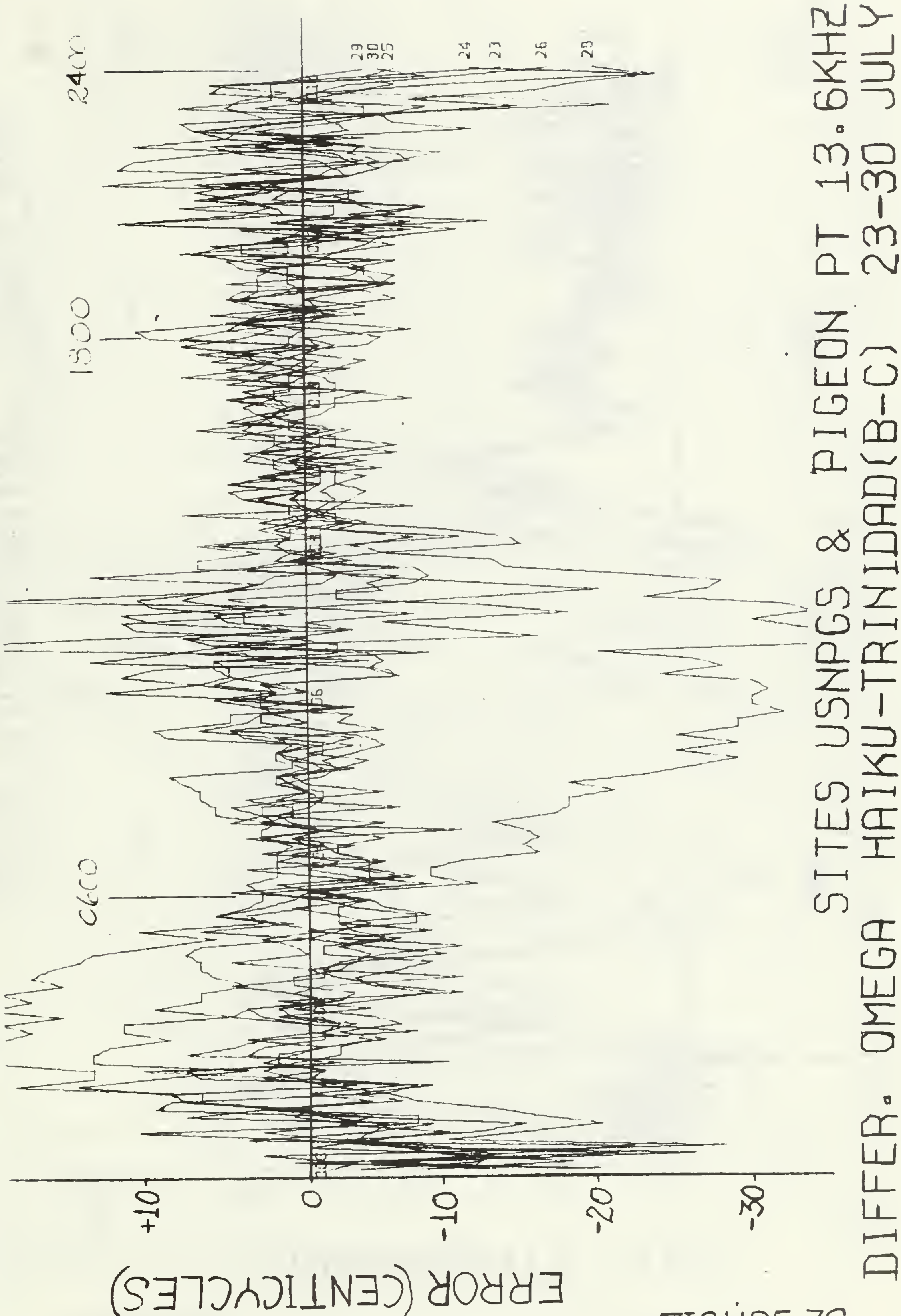
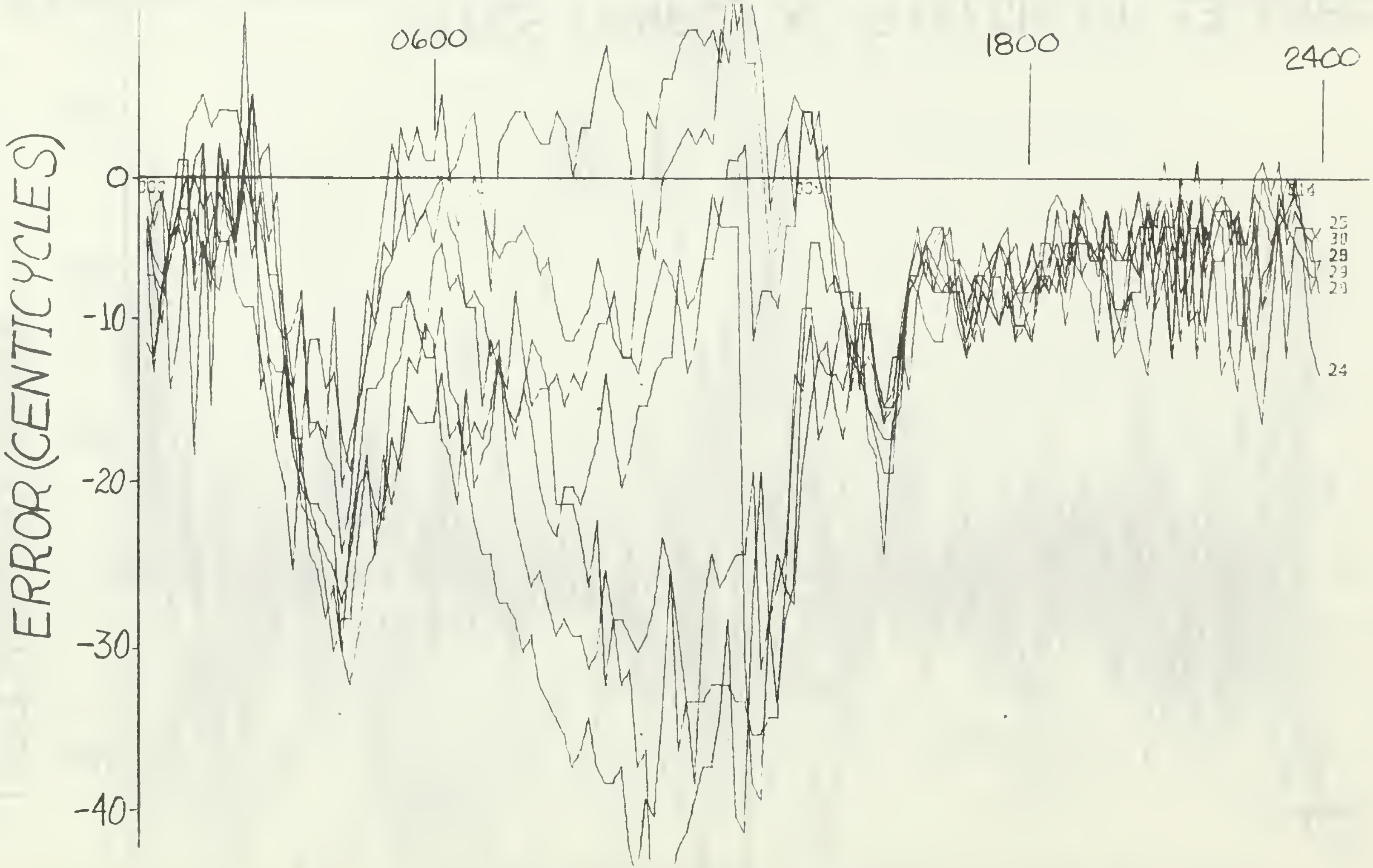

SITES USNPGS & PIGEON PT 13.6KHZ
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) 23-30 JULY
ERROR (CENTICYCLES)
+10
0
-10
-20
-30
0600
1800
2400
29
30
25
24
23
26
23

FIGURE 38



SITE PIGEON POINT 13.6 KHZ
SKYWAVE CORR. HAIKU-FOR'PORT(C-D) 23-30 JUL

FIGURE 39

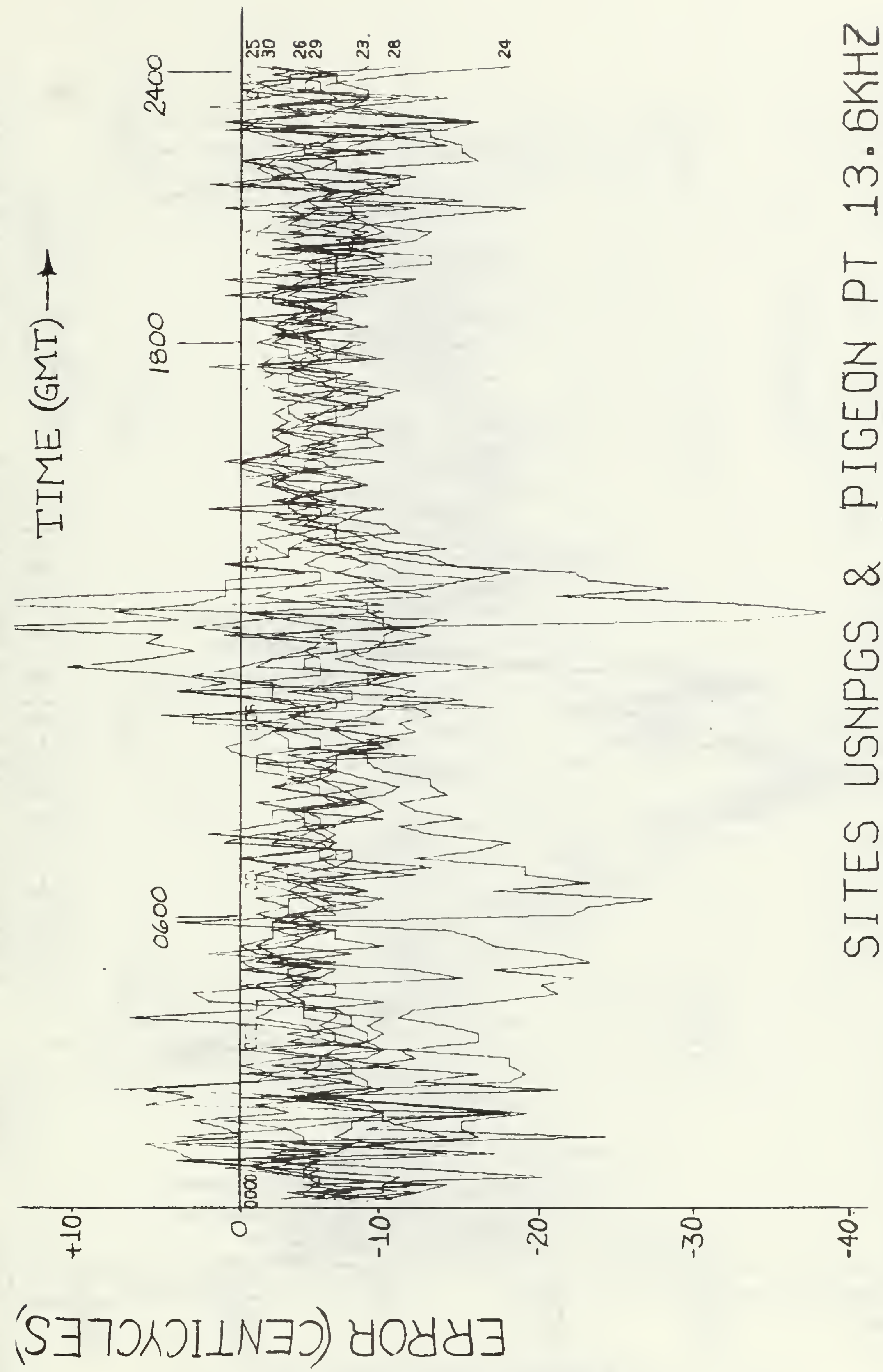

SITES USNPGS & PIGEON PT 13.6KHZ
DIF.OMEGA HAIKU-FOR'PORT(C-D) 23-30 JULY
TIME (GMT)
ERROR (CENTICYCLES)
0600
1800
2400
+10
0
-10
-20
-30
-40

FIGURE 40

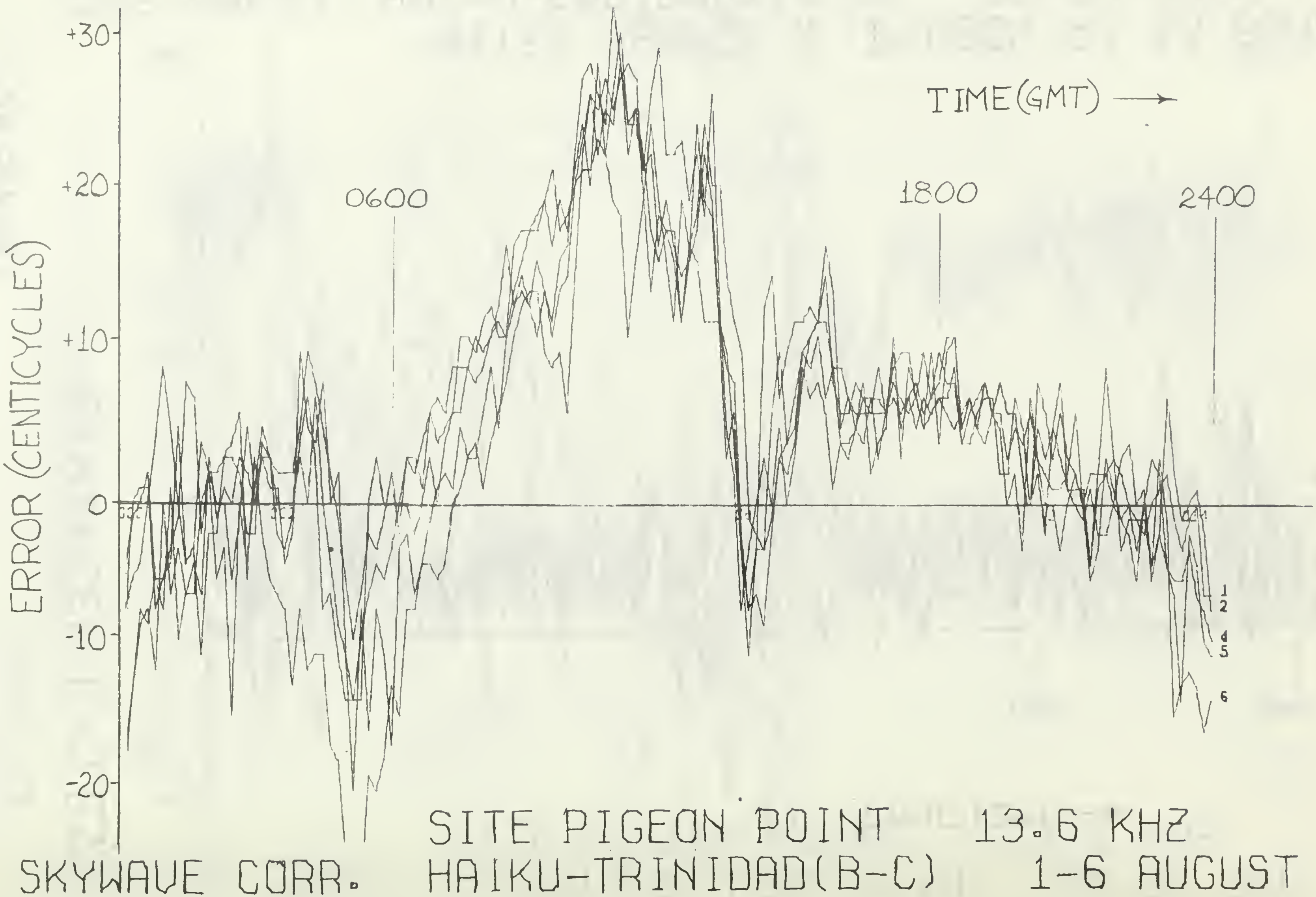

TIME(GMT)
+30
+20
+10
0
-10
-20
ERROR (CENTICYCLES)
0600
1800
2400
1
2
4
5
6
SITE PIGEON POINT 13.6 KHZ
SKYWAVE CORR. HAIKU-TRINIDAD(B-C) 1-6 AUGUST

FIGURE 41

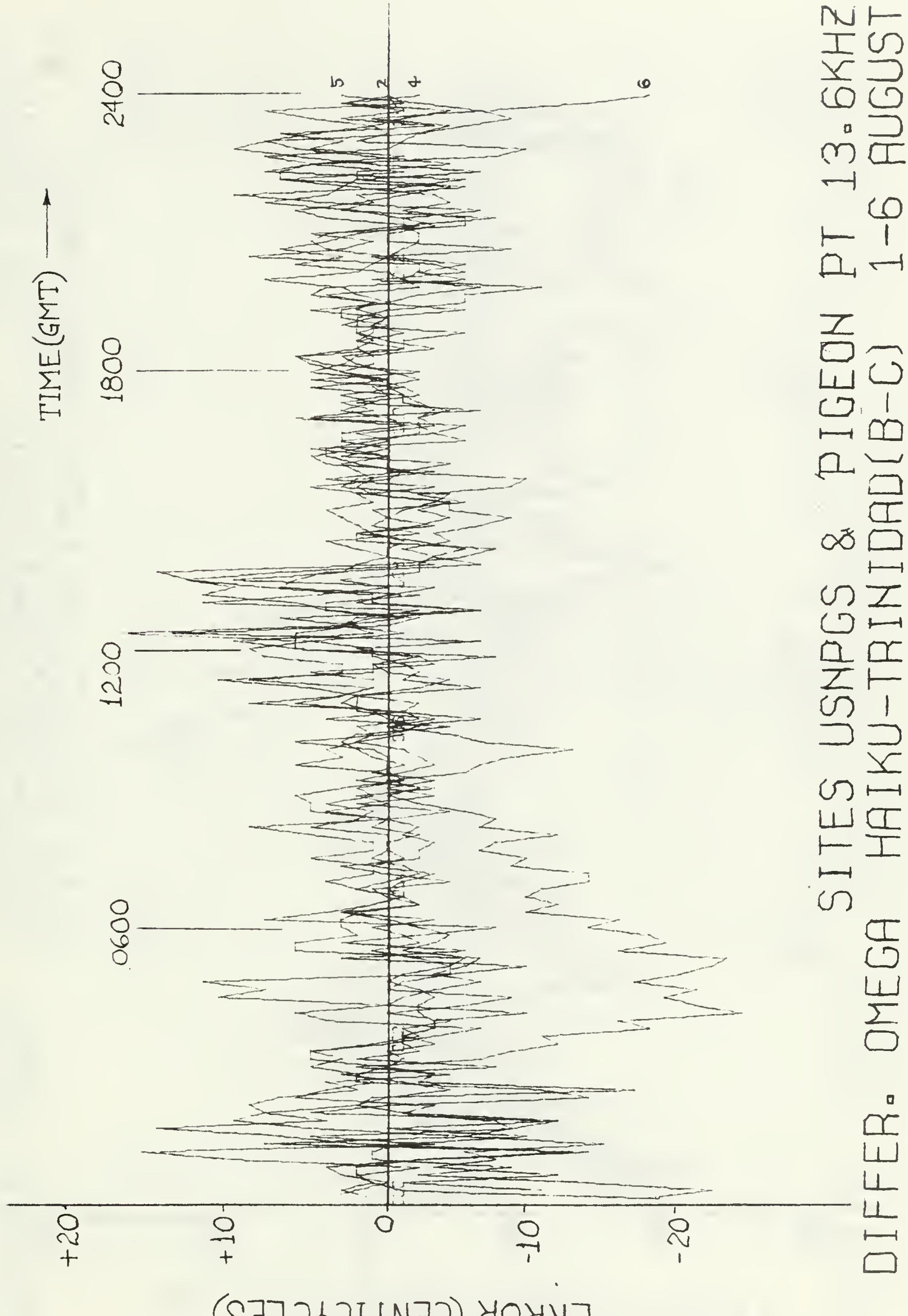

SITES USNPGS & PIGEON PT 13.6KHZ
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) 1-6 AUGUST
TIME (GMT)
0600
1200
1800
2400
5
2
4
6
+20
+10
0
-10
-20
ERROR (CENTICYCLES)

FIGURE 42

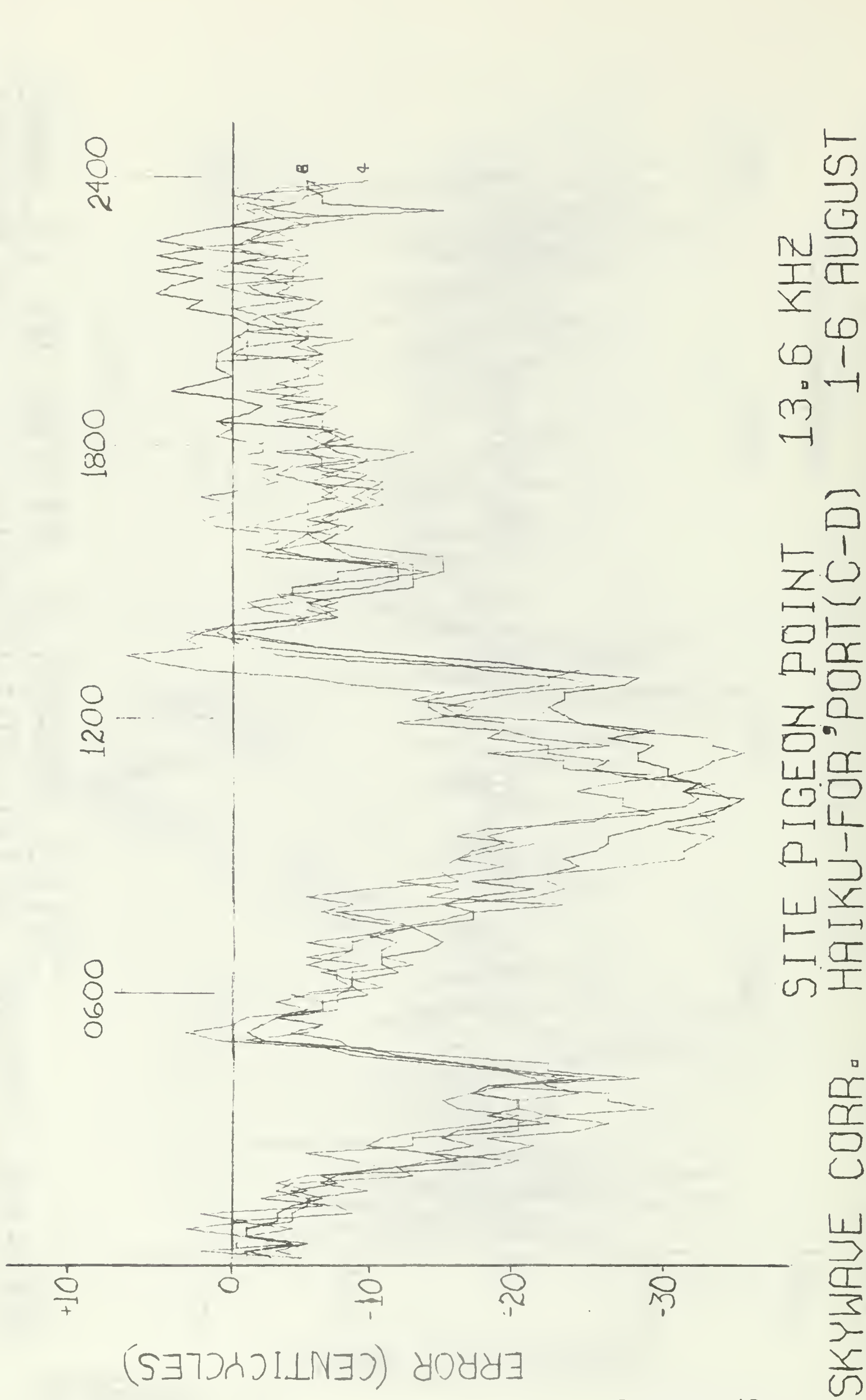
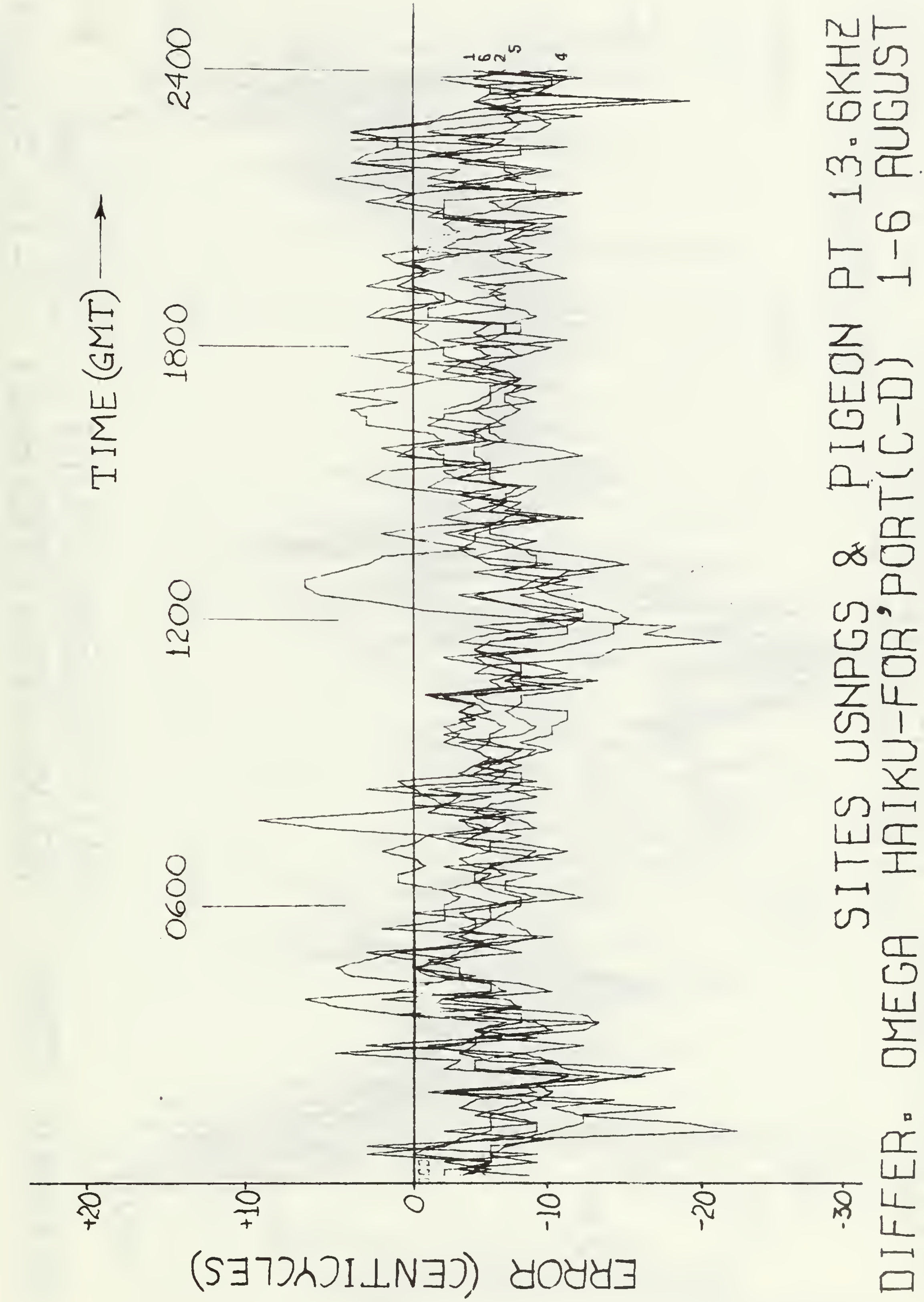

SITE PIGEON POINT 13.6 KHZ
SKYWAVE CORR. HAIKU-FOR'PORT(C-D) 1-6 AUGUST
ERROR (CENTICYCLES)
+10
0
-10
-20
-30
0600
1200
1800
2400

FIGURE 43



TIME (GMT) →
0600
1200
1800
2400
+20
+10
0
-10
-20
-30
ERROR (CENTICYCLES)
1
6
2
5
4
SITES USNPGS & PIGEON PT 13.6KHZ
DIFFER. OMEGA HAIKU-FOR'PORT(C-D) 1-6 AUGUST

FIGURE 44

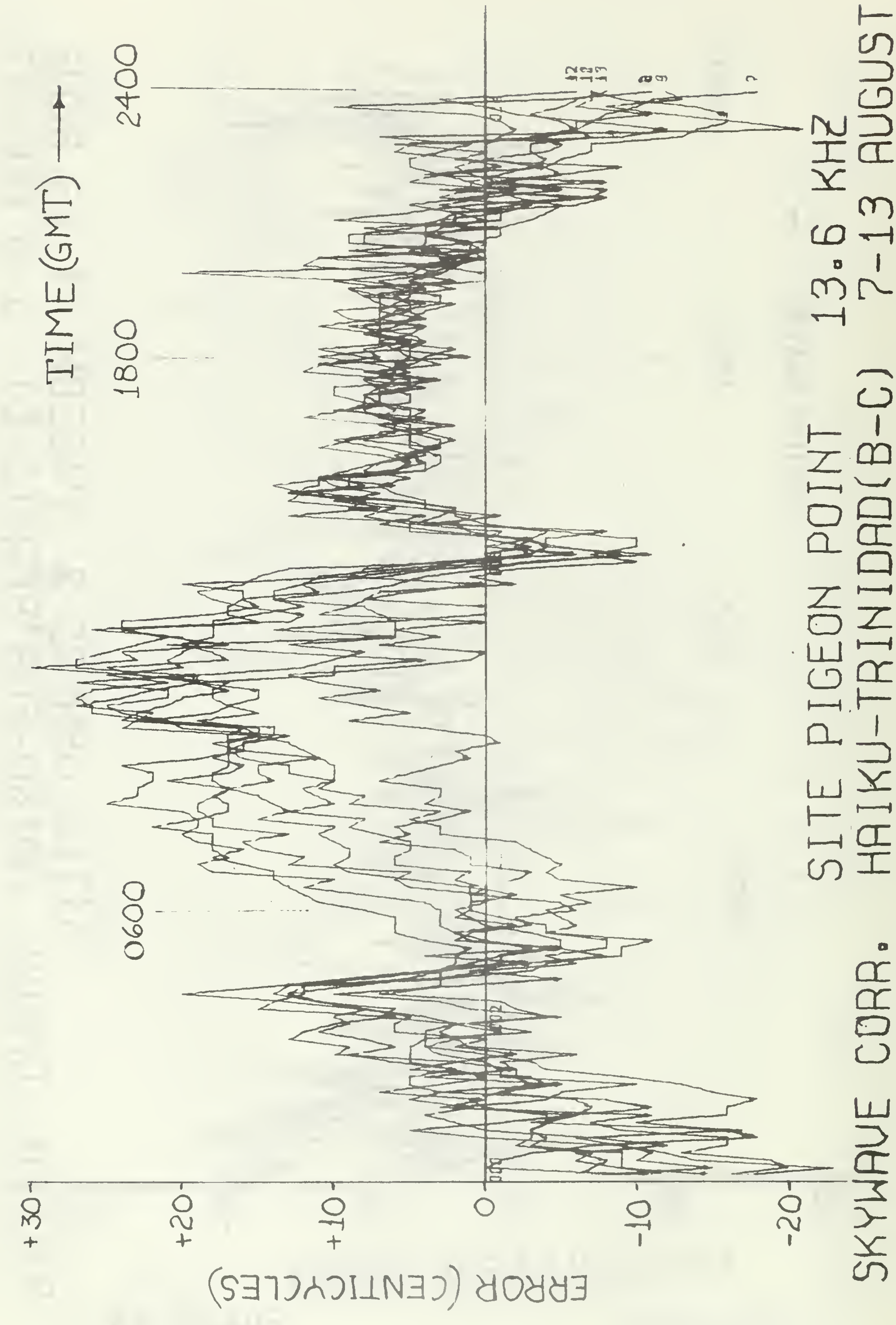
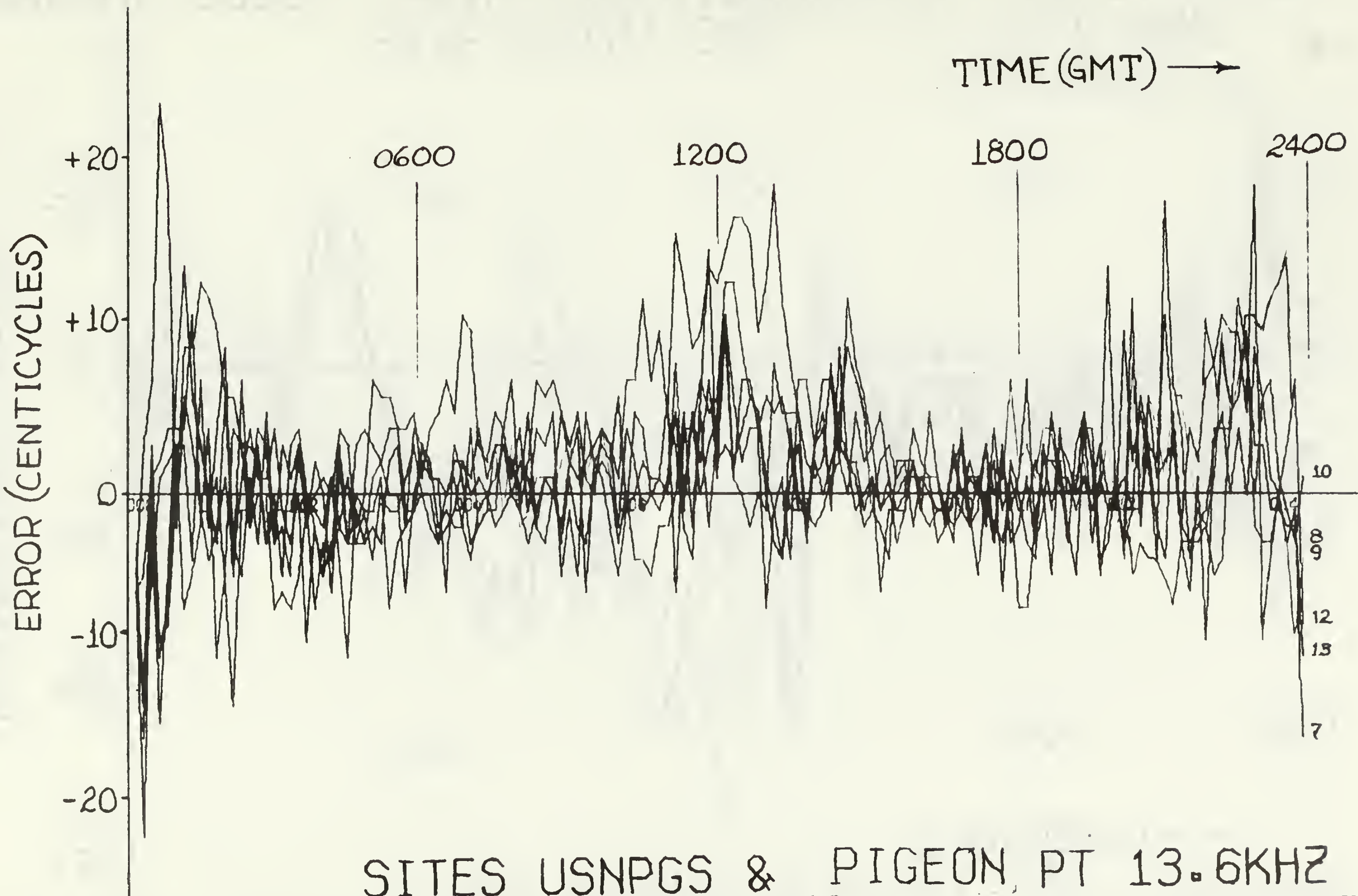
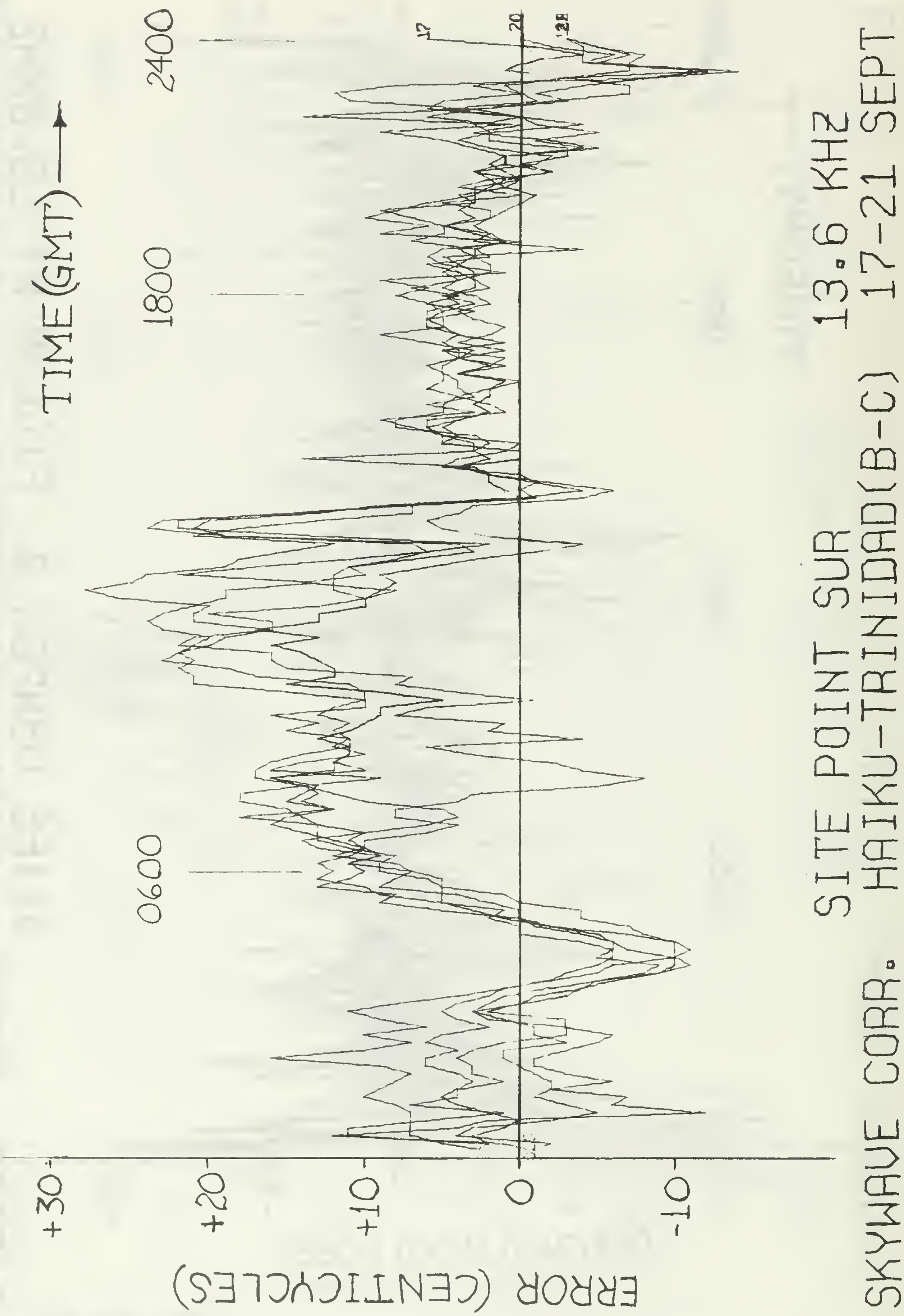

SKYWAVE CORR. SITE PIGEON POINT 13.6 KHZ
HAIKU-TRINIDAD(B-C) 7-13 AUGUST
TIME (GMT)
0600
1800
2400
ERROR (CENTICYCLES)
+30
+20
+10
0
-10
-20

FIGURE 45



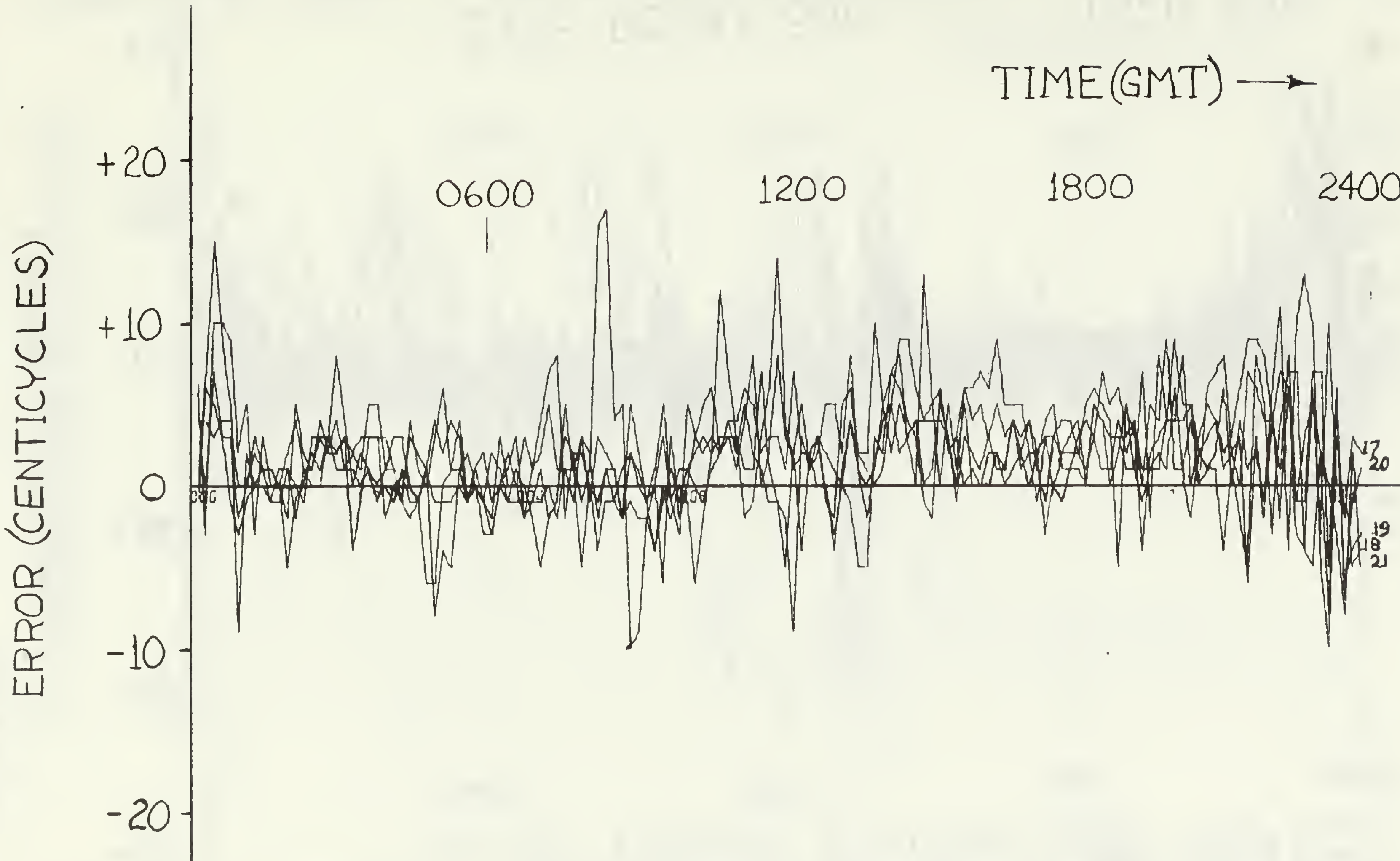
SITES USNPGS & PIGEON PT 13.6KHZ
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) 7-13 AUGUST

FIGURE 46



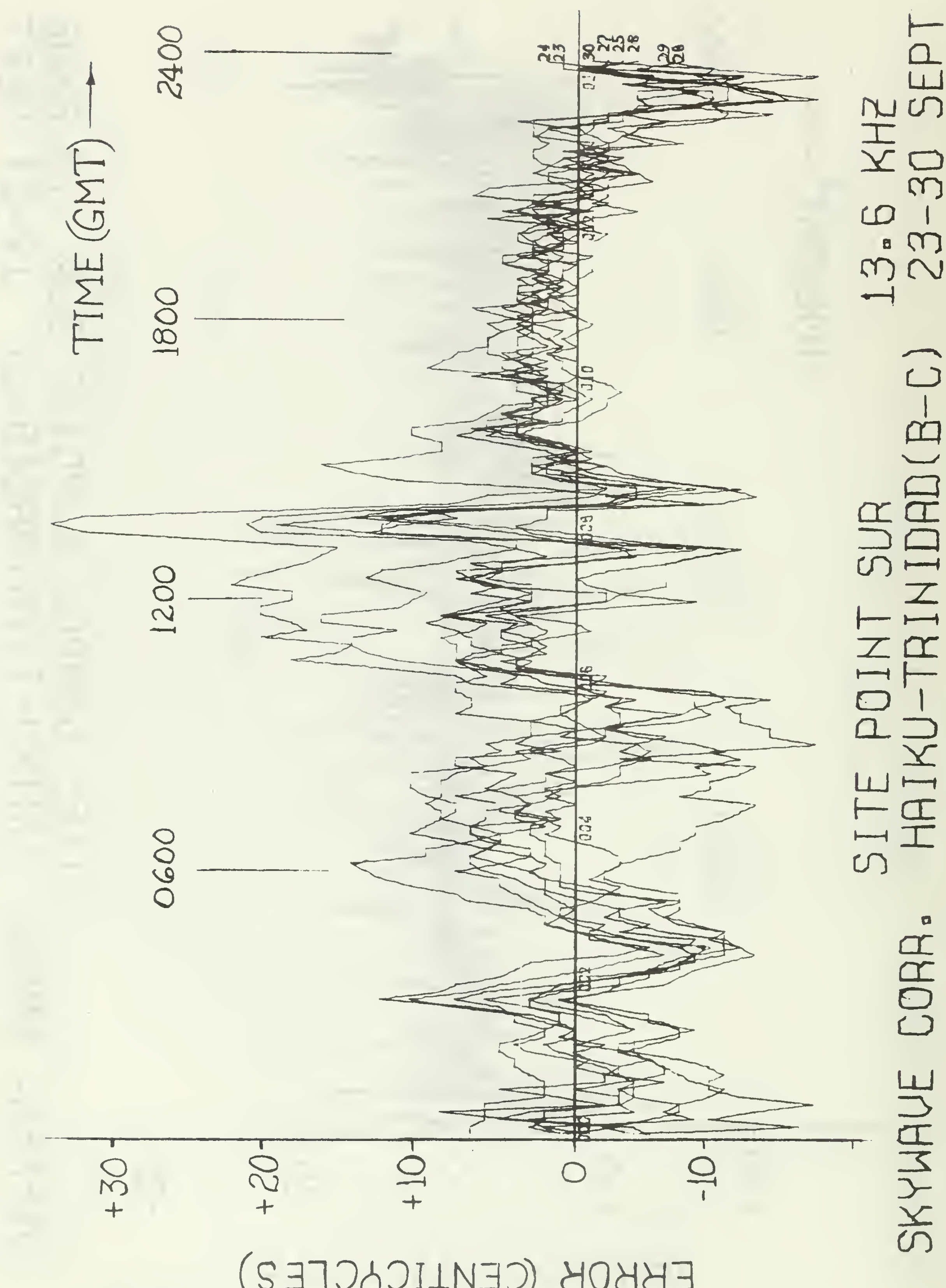
TIME (GMT)
0600
1800
2400
+30
+20
+10
0
-10
ERROR (CENTICYCLES)
SITE POINT SUR 13.6 KHZ
SKYWAVE CORR. HAIKU-TRINIDAD(B-C) 17-21 SEPT

FIGURE 47



SITES USNPGS & POINT SUR 13.6KHZ
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) 17-21 SEPT

FIGURE 48



TIME (GMT)
0600
1200
1800
2400
+30
+20
+10
0
-10
ERROR (CENTICYCLES)
SITE POINT SUR 13.6 KHZ
SKYWAVE CORR. HAIKU-TRINIDAD(B-C) 23-30 SEPT

FIGURE 49

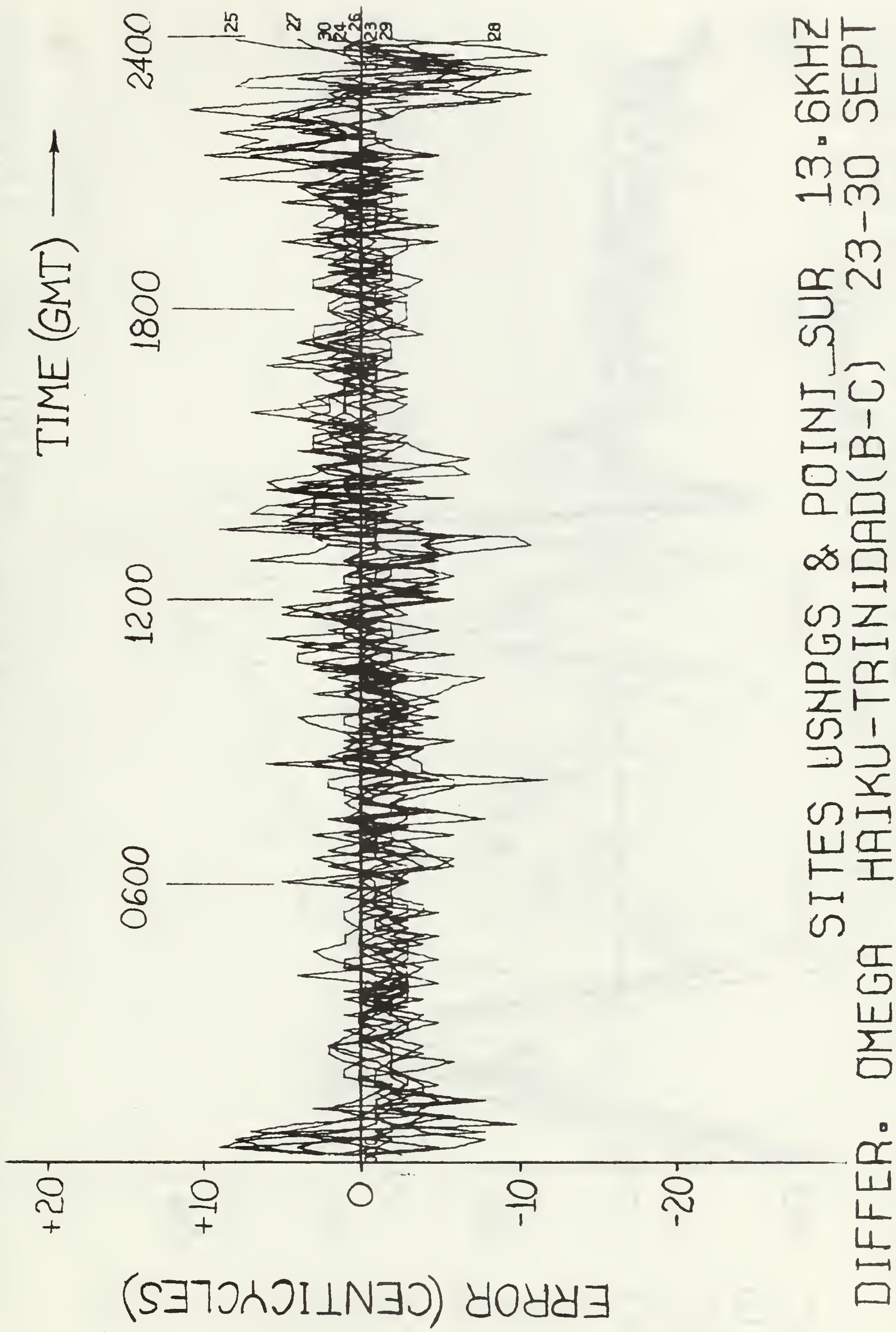
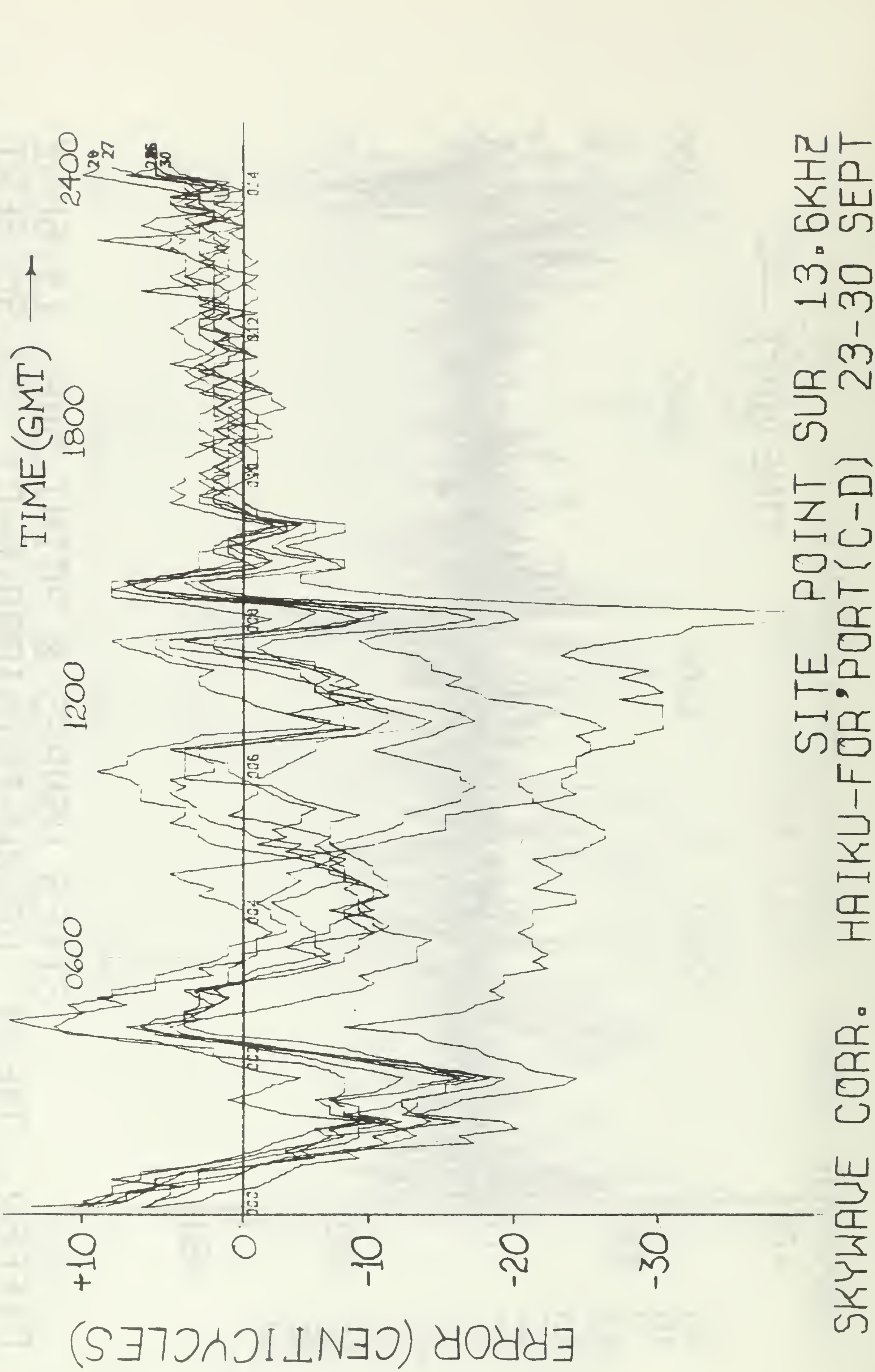
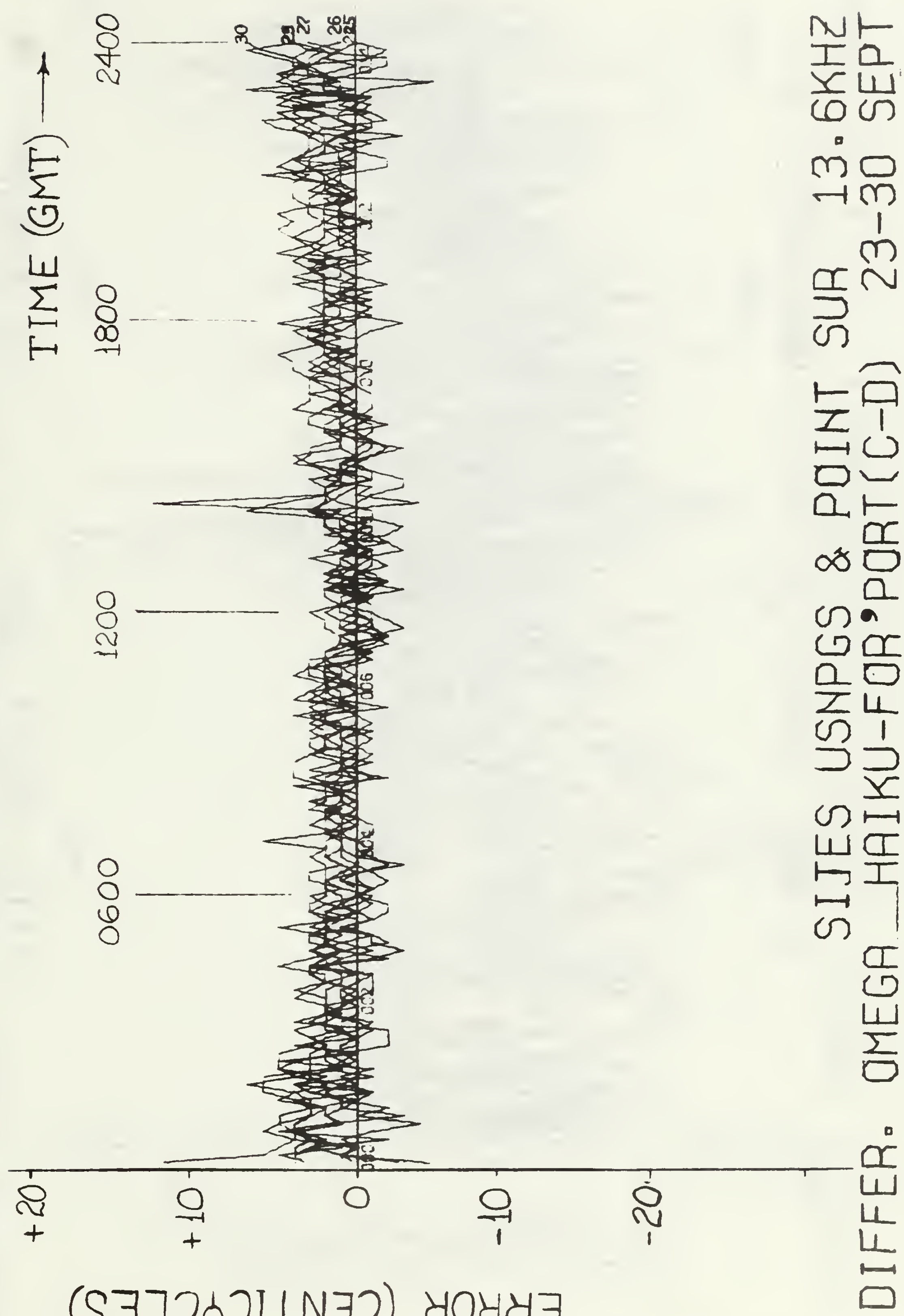

TIME (GMT)
0600
1200
1800
2400
25
27
30
24
26
23
29
28
ERROR (CENTICYCLES)
+20
+10
0
-10
-20
SITES USNPGS & POINT SUR 13.6KHZ
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) 23-30 SEPT

FIGURE 50



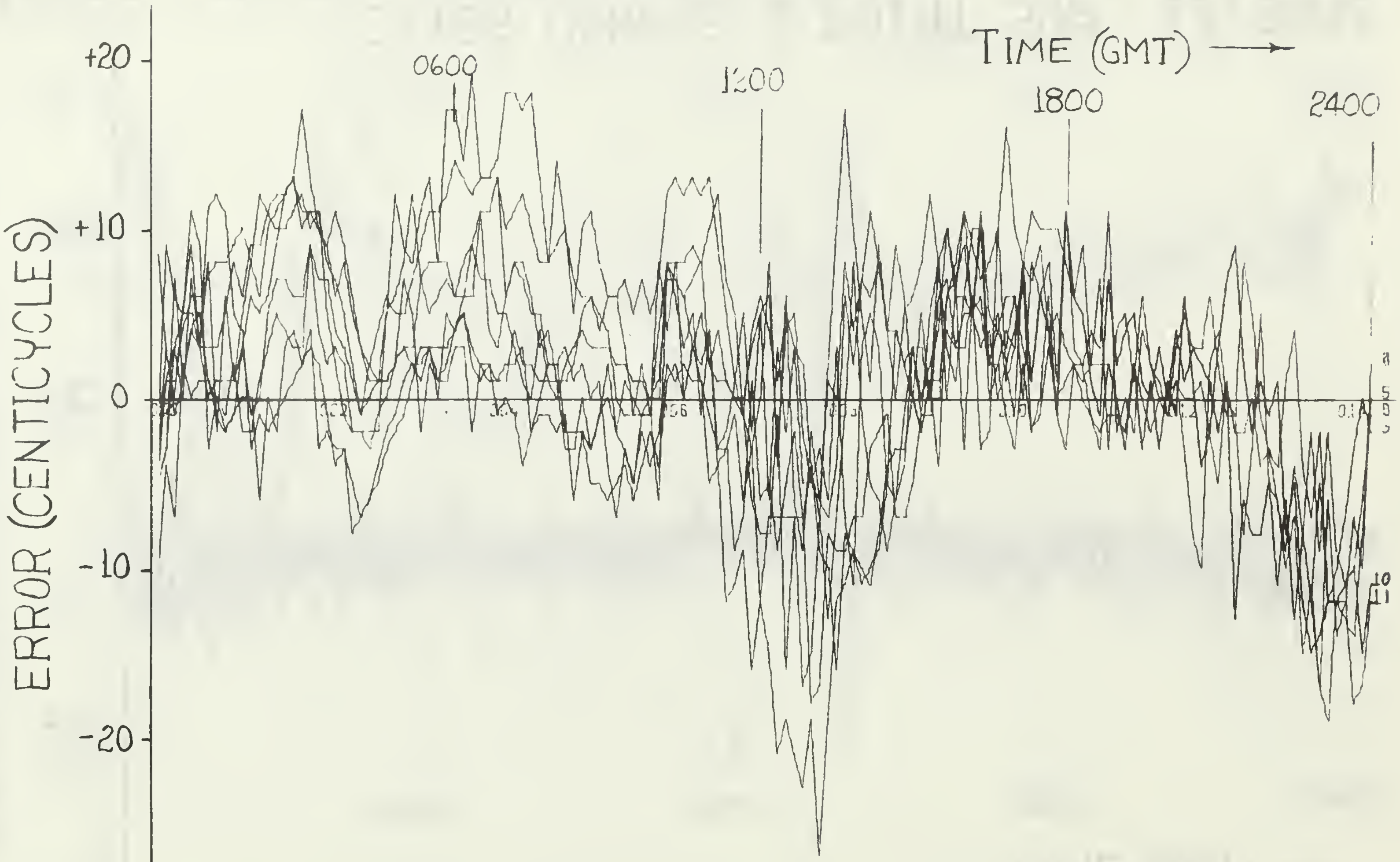
TIME (GMT)
0600
1200
1800
2400
+10
0
-10
-20
-30
ERROR (CENTICYCLES)
SKYWAVE CORR. SITE POINT SUR 13.6KHZ
HAIKU-FOR'PORT(C-D) 23-30 SEPT

FIGURE 51



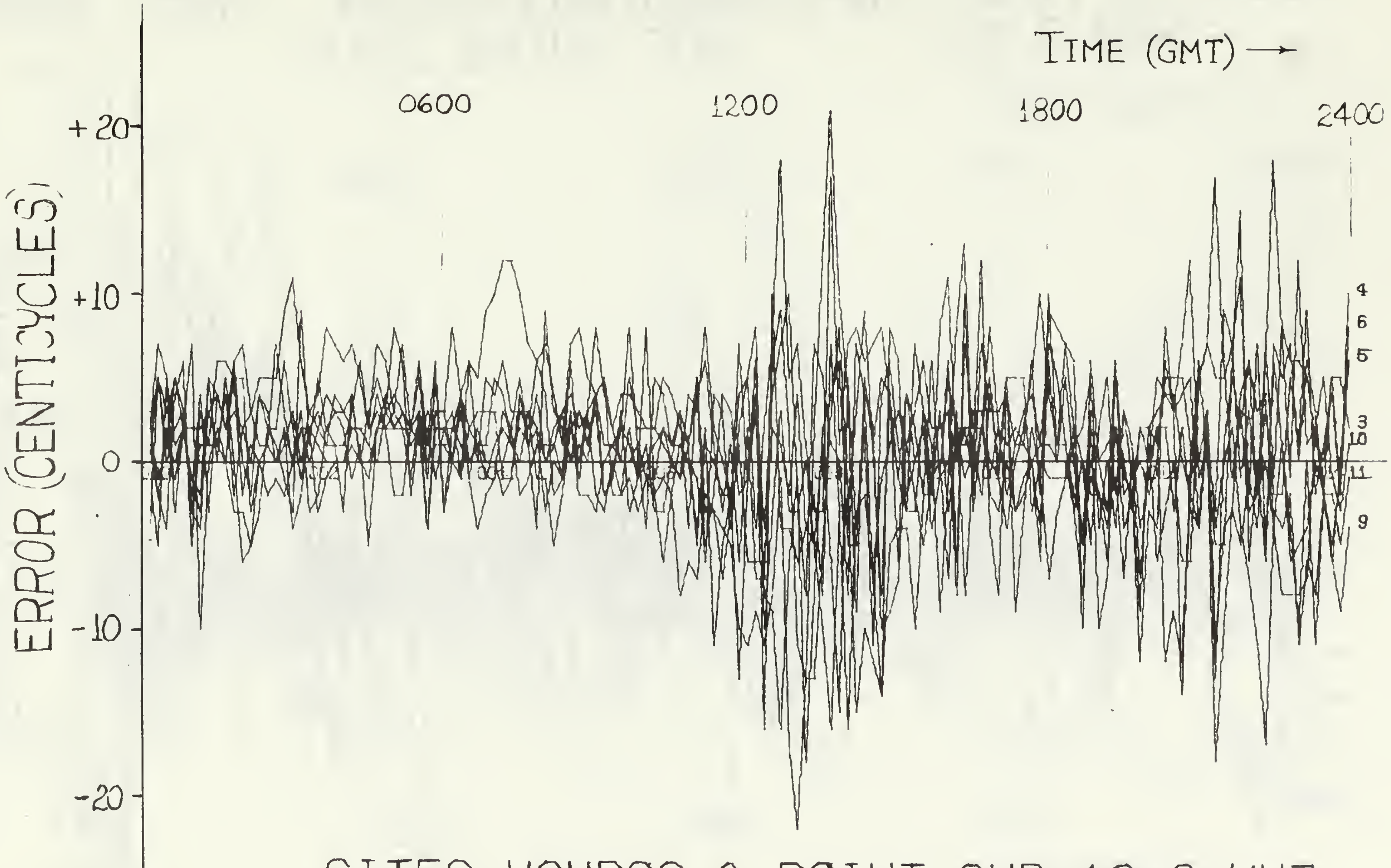
TIME (GMT)
0600
1200
1800
2400
+20
+10
0
-10
-20
ERROR (CENTICYCLES)
SIJES USNPGS & POINT SUR 13.6KHZ
DIFFER. OMEGA HAIKU-FOR'PORT(C-D) 23-30 SEPT

FIGURE 52



SITE POINT SUR 10.2 KHZ
SKYWAVE CORR. HAIKU-TRINIDAD(B-C) 3-11 OCTOBER

FIGURE 53



SITES USNPGS & POINT SUR 10.2 KHZ
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) 3-11 OCTOBER

FIGURE 54

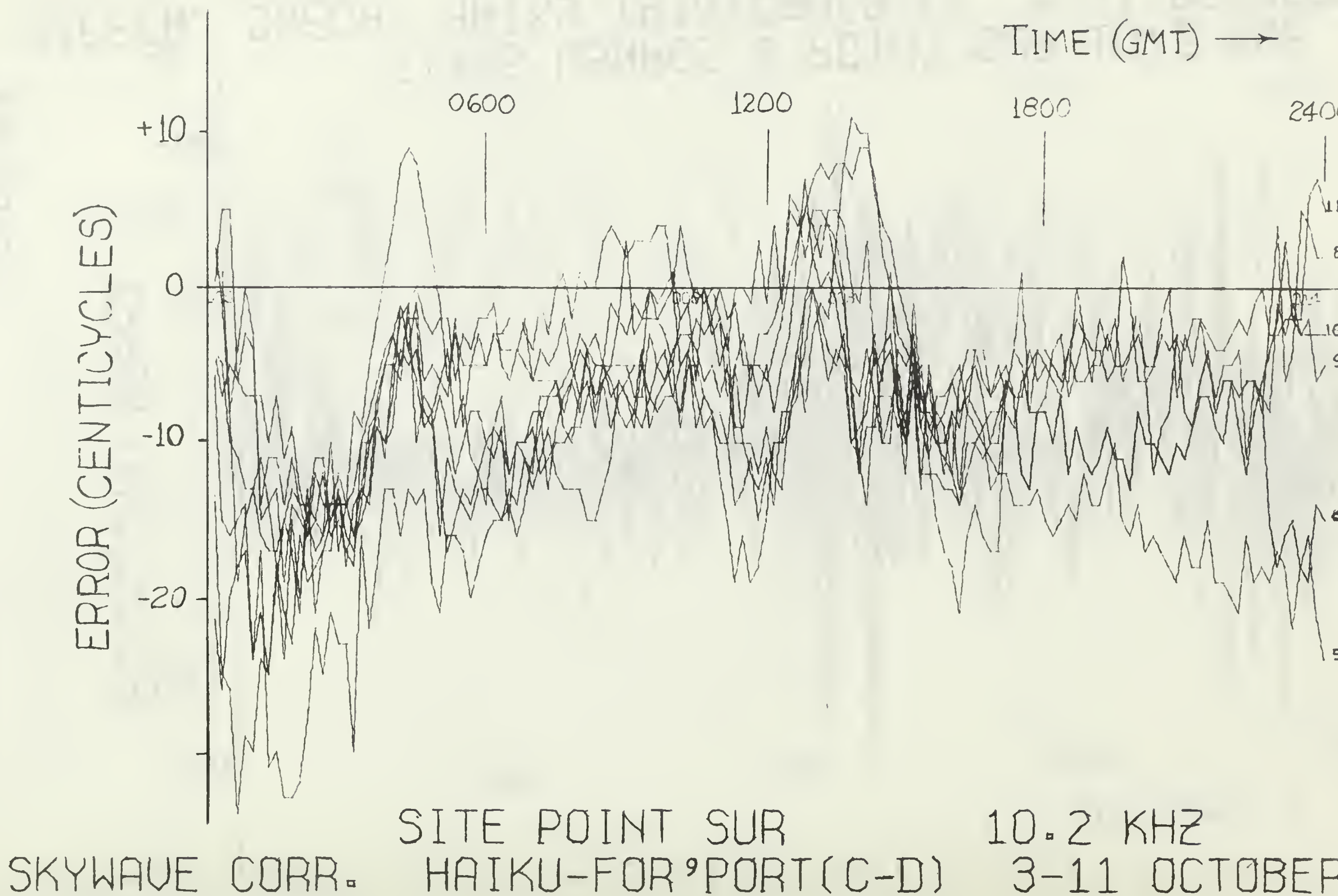
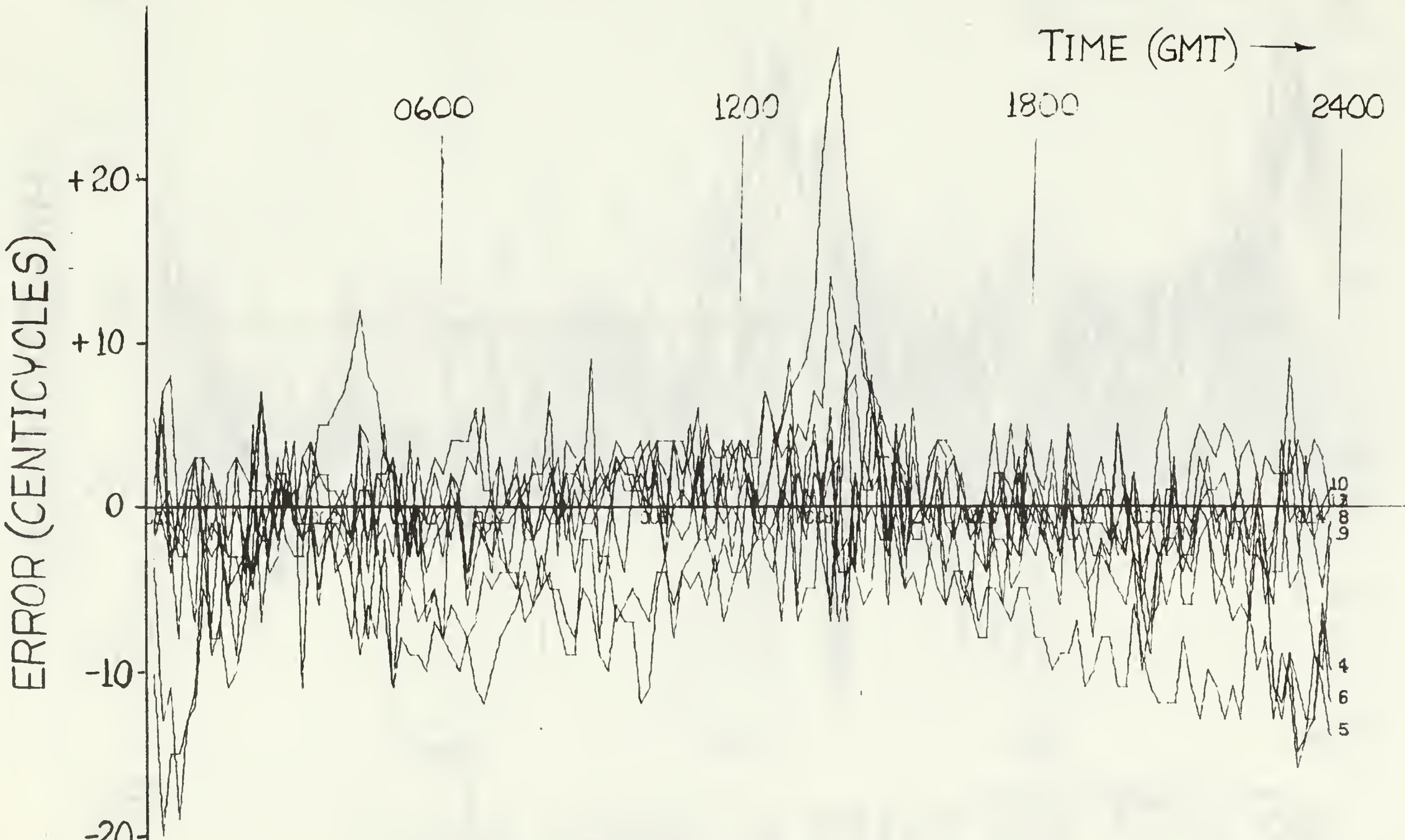

TIME (GMT) →
0600
1200
1800
2400
+10
0
-10
-20
ERROR (CENTICYCLES)
11
8
10
9
4
5
SITE POINT SUR 10.2 KHZ
SKYWAVE CORR. HAIKU-FOR'PORT(C-D) 3-11 OCTOBER

FIGURE 55



SITES USNPGS & POINT SUR 10.2 KHZ
DIFFER. OMEGA HAIKU-FOR'PORT(C-D) 3-11 OCTOBER

FIGURE 56

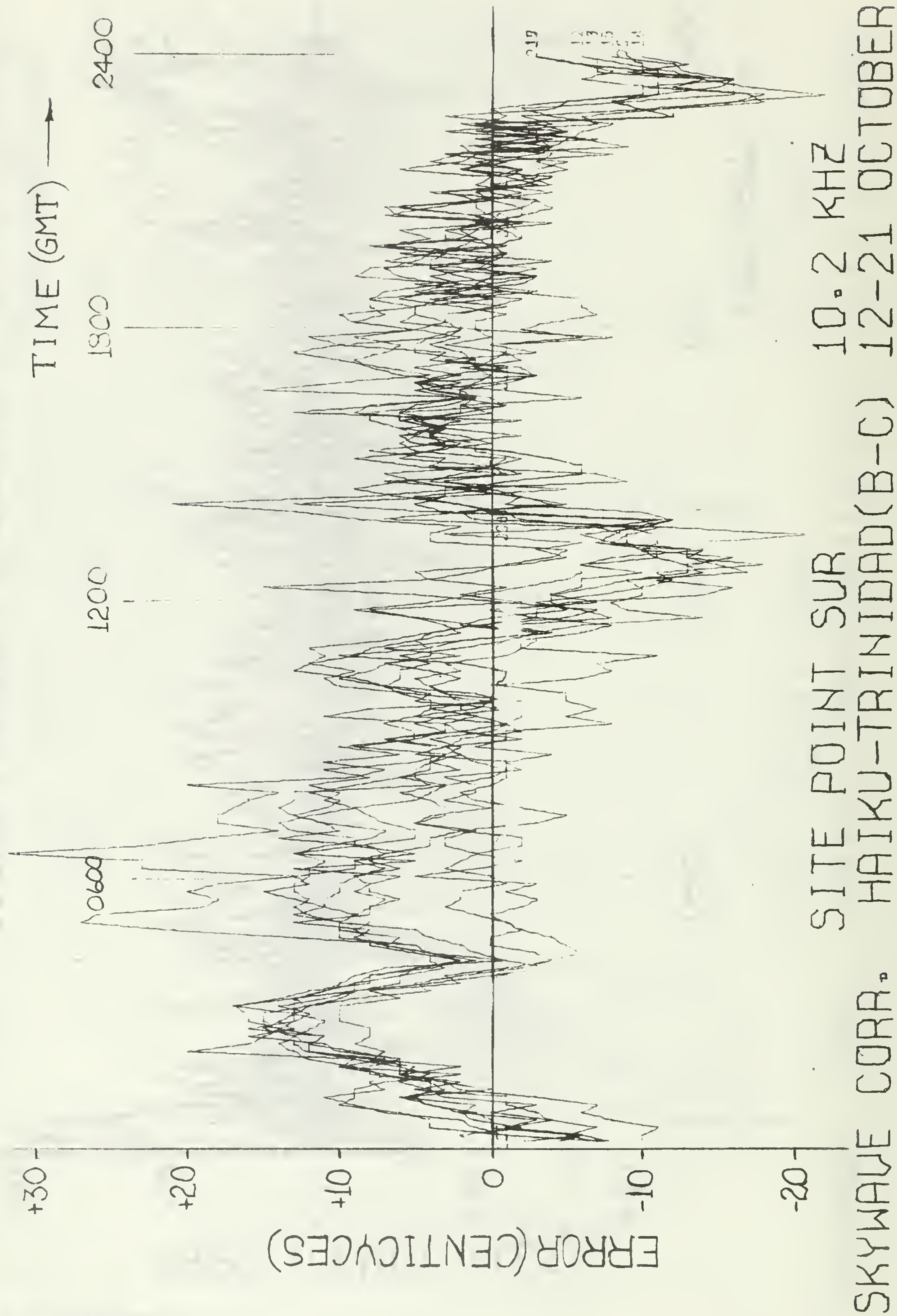
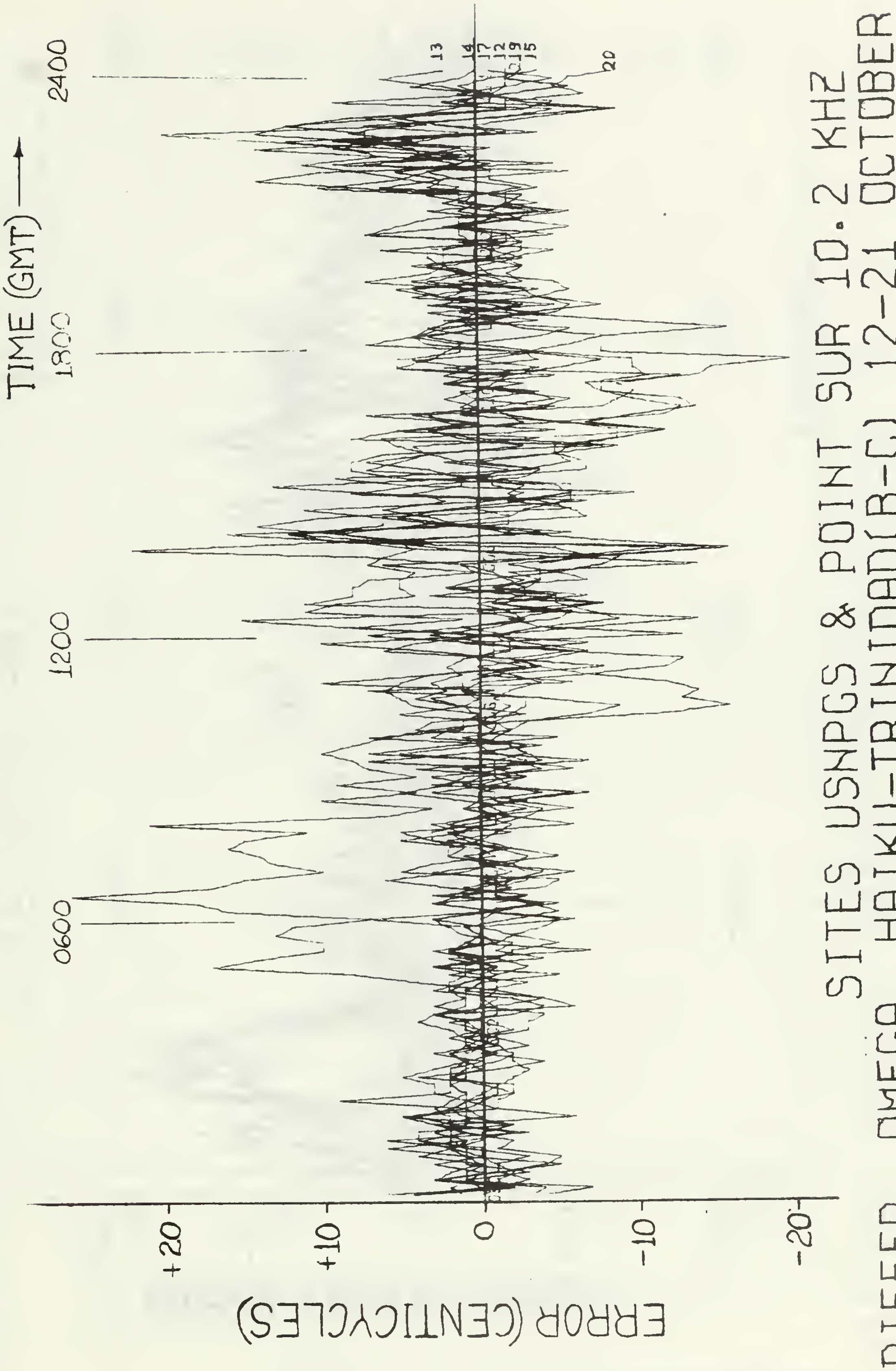

SKYWAVE CORR. SITE POINT SUR 10.2 KHZ
HAIKU-TRINIDAD(B-C) 12-21 OCTOBER
TIME (GMT)
0600
1200
1800
2400
ERROR (CENTICYCLES)
+30
+20
+10
0
-10
-20

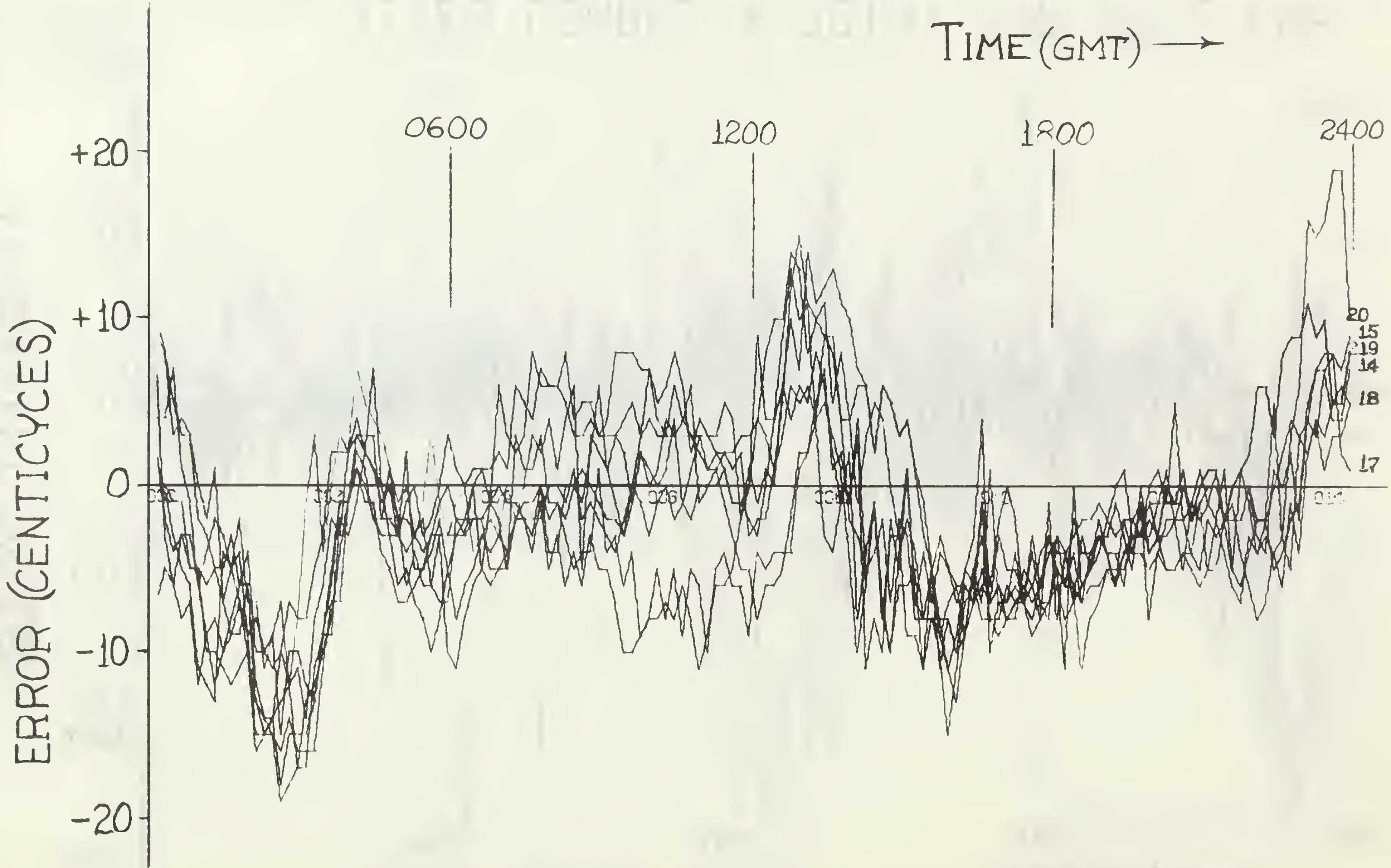
FIGURE 57



TIME (GMT)
0600
1200
1800
2400
+20
+10
0
-10
-20
ERROR (CENTICYCLES)
SITES USNPGS & POINT SUR 10.2 KHZ
DIFFER. OMEGA HAIKU-TRINIDAD(B-C) 12-21 OCTOBER

FIGURE 58

FIGURE 59

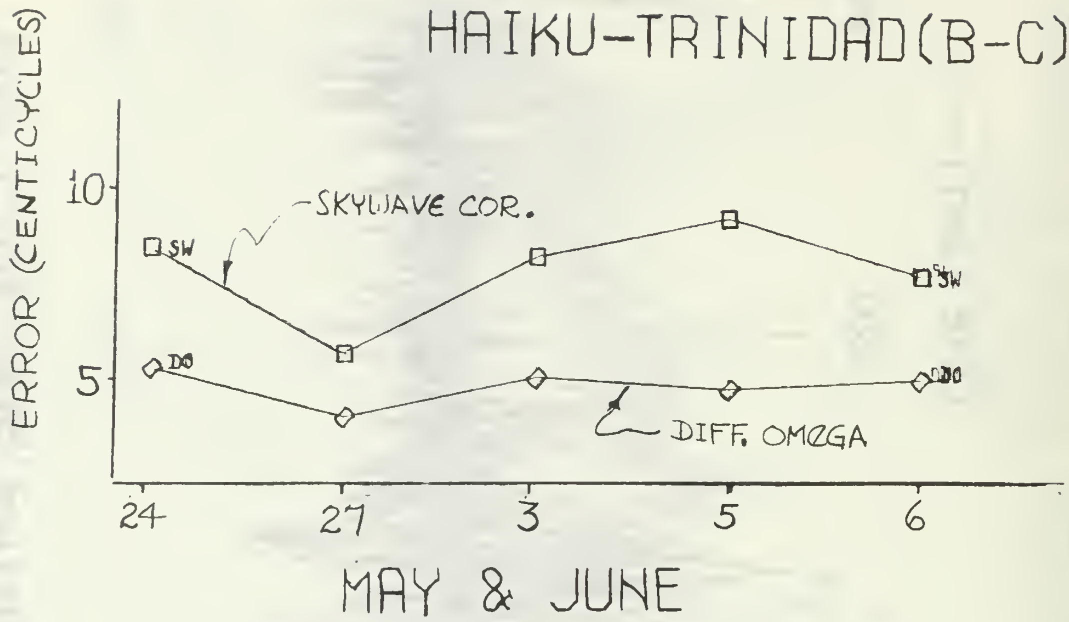


SITE POINT SUR 10.2 KHZ
SKYWAVE CORR. HAIKU-FOR'PORT (C-D) 12-21 OCTØBER

SITES USNPGS & POINT SUR 10.2 KHZ
DIFFER. OMEGA HAIKU-FOR'PORT(C-D) 12-21 OCTOBER
TIME (GMT)
0600
1200
1800
2400
ERROR (CENTICYCLES)
+20
+10
0
-10
-20

FIGURE 60

HAIKU-TRINIDAD(B-C)



COMPARISON DIF OMEGA VS. SKYWAVE
CORRECTED AVERAGE ERROR 10.2KHZ
SITE PIGEON POINT

HAIKU-FOR'PORT(C-D)

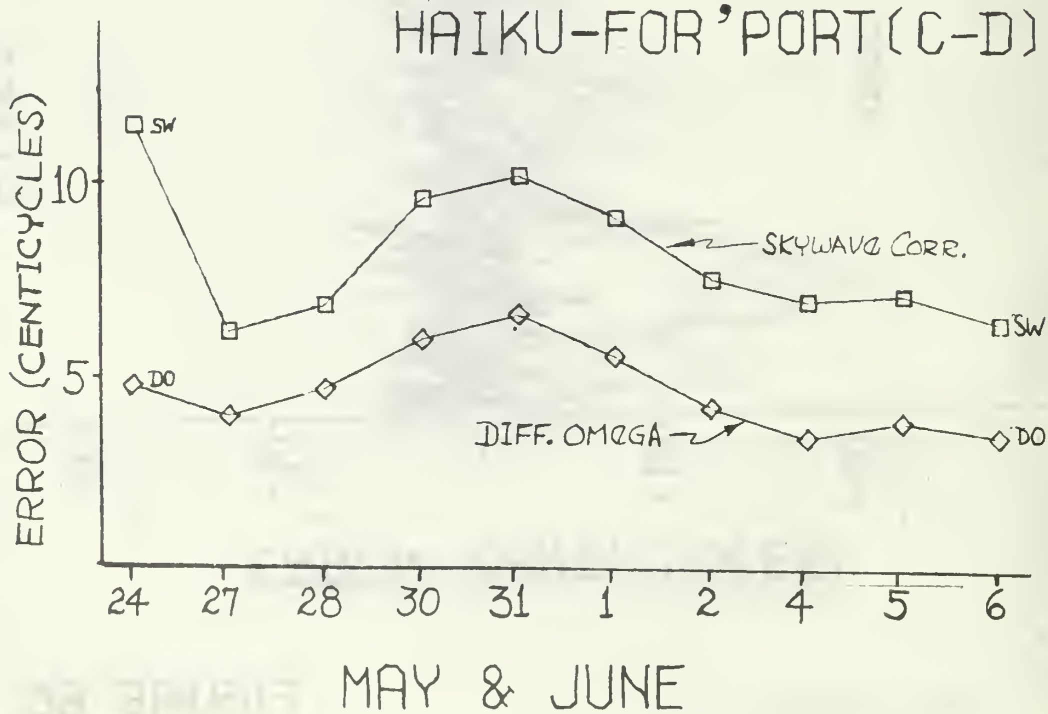
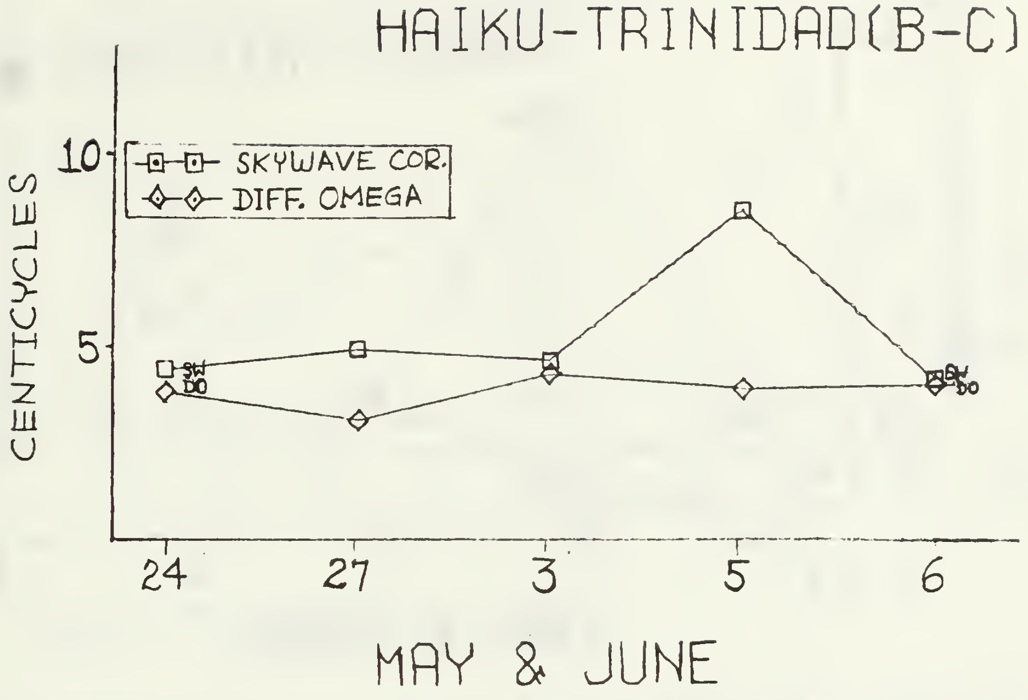


FIGURE 61



PIGEON POINT
COMPARISON DIF OMEGA VS. SKYWAVE
COR. STANDARD DEVIATION 10.2KHZ

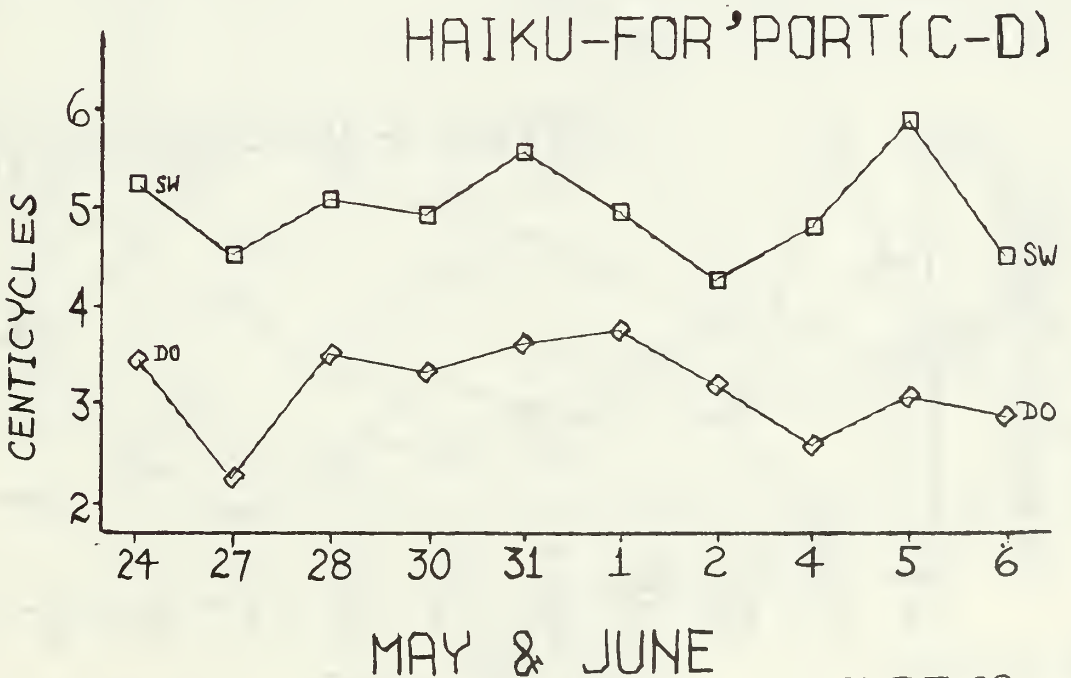
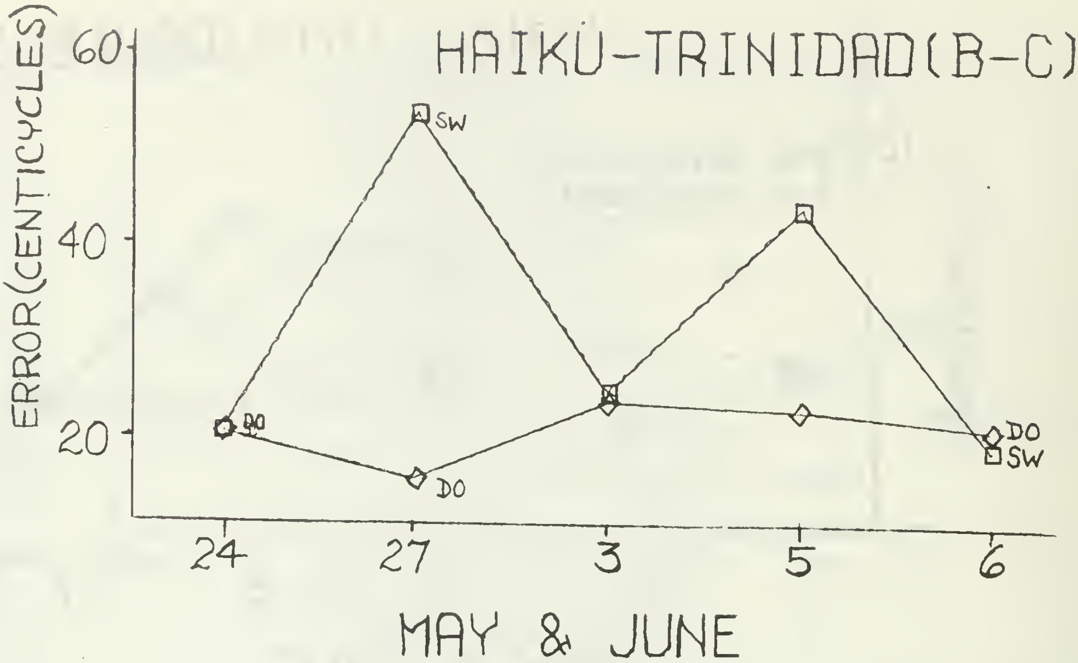


FIGURE 62



SITE PIGEON POINT

COMPARISON DIF OMEGA VS SKYWAVE

COR. MAXIMUM ERROR 10.2 KHZ

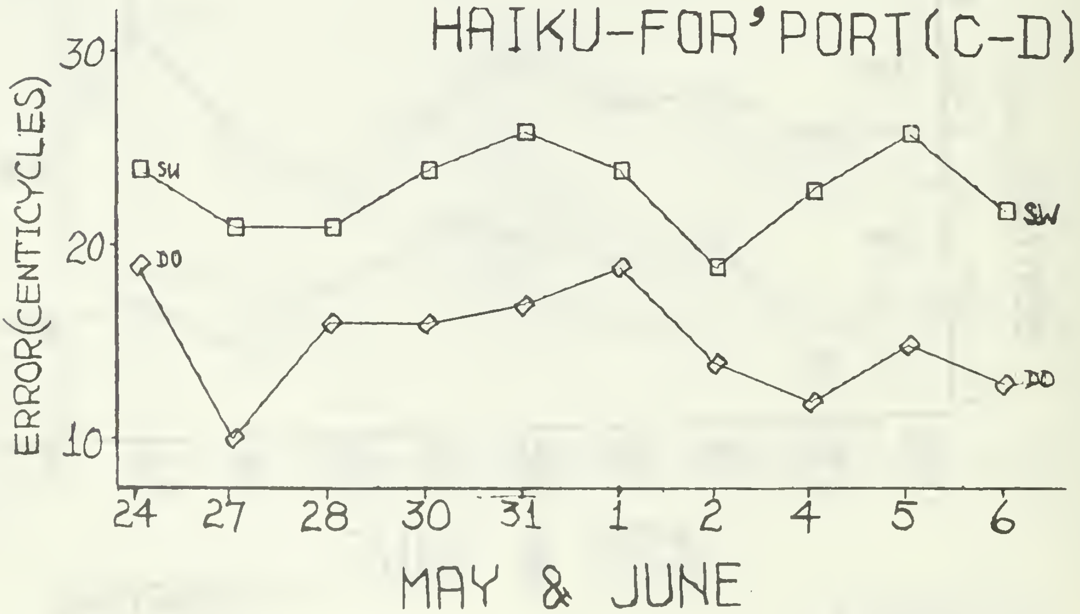


FIGURE 63

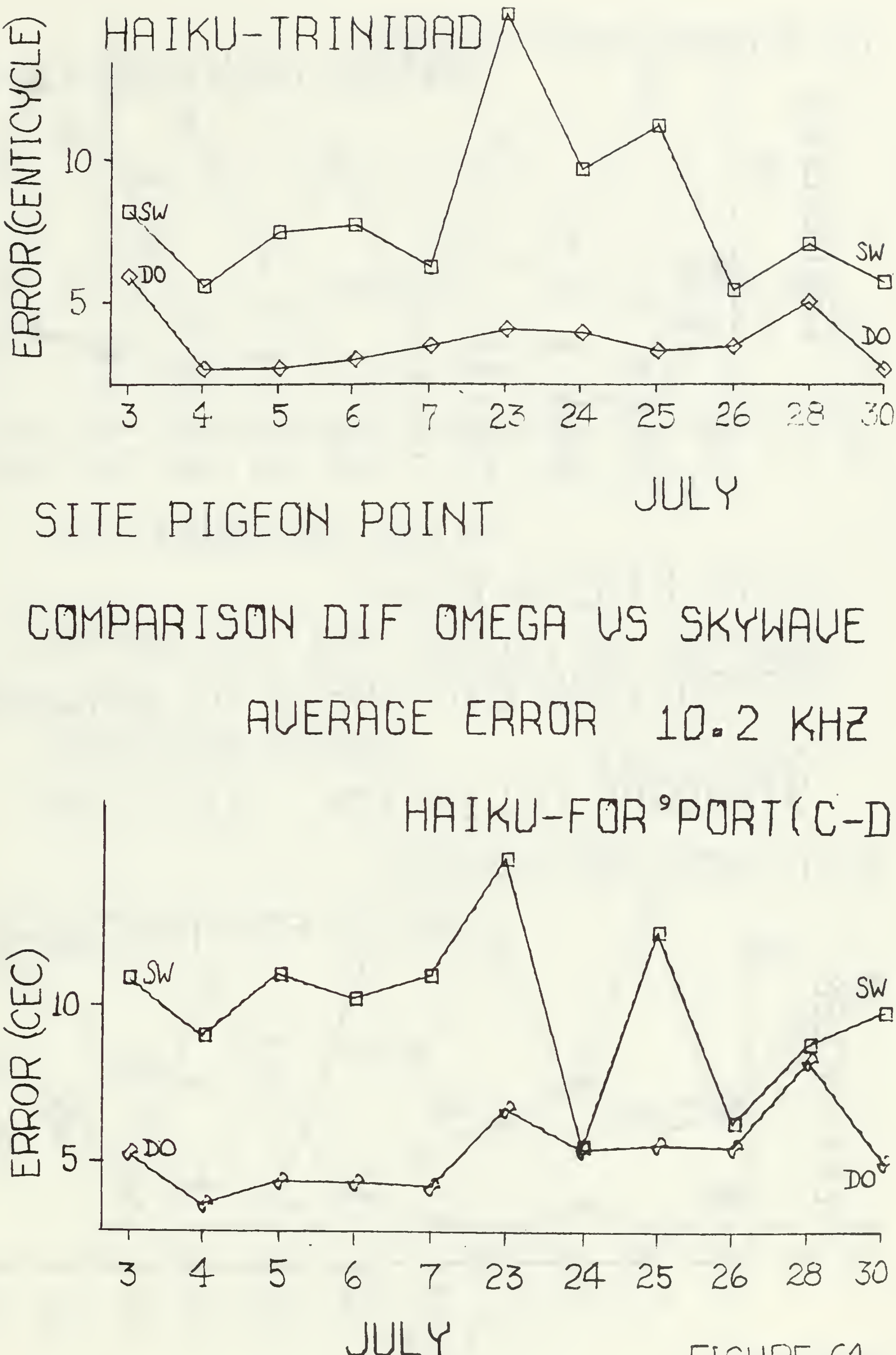
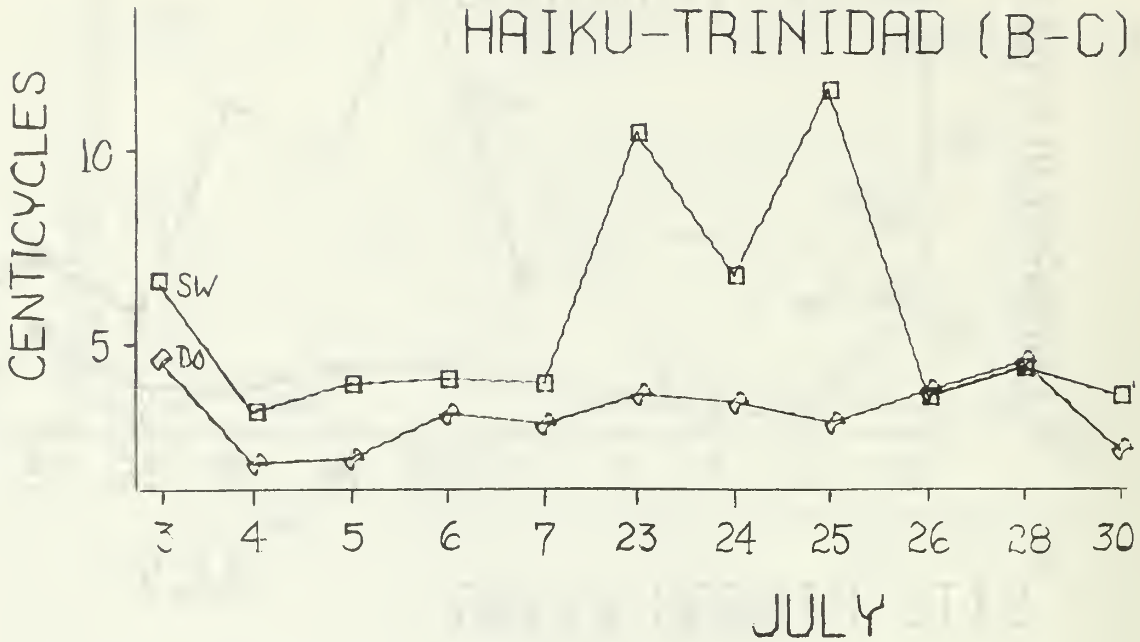

HAIKU-TRINIDAD
ERROR (CENTICYCLE)
10
5
SW
DO
SW
DO
3
4
5
6
7
23
24
25
26
28
30
JULY
SITE PIGEON POINT
COMPARISON DIF OMEGA VS SKYWAVE
AVERAGE ERROR 10.2 KHZ
HAIKU-FOR'PORT(C-D
ERROR (CEC)
10
5
SW
DO
SW
DO
3
4
5
6
7
23
24
25
26
28
30
JULY

FIGURE 64



SITE PIGEON POINT

COMPARISON DIF OMEGA VS SKYWAVE

STANDARD DEVIATION 10.2 KHZ

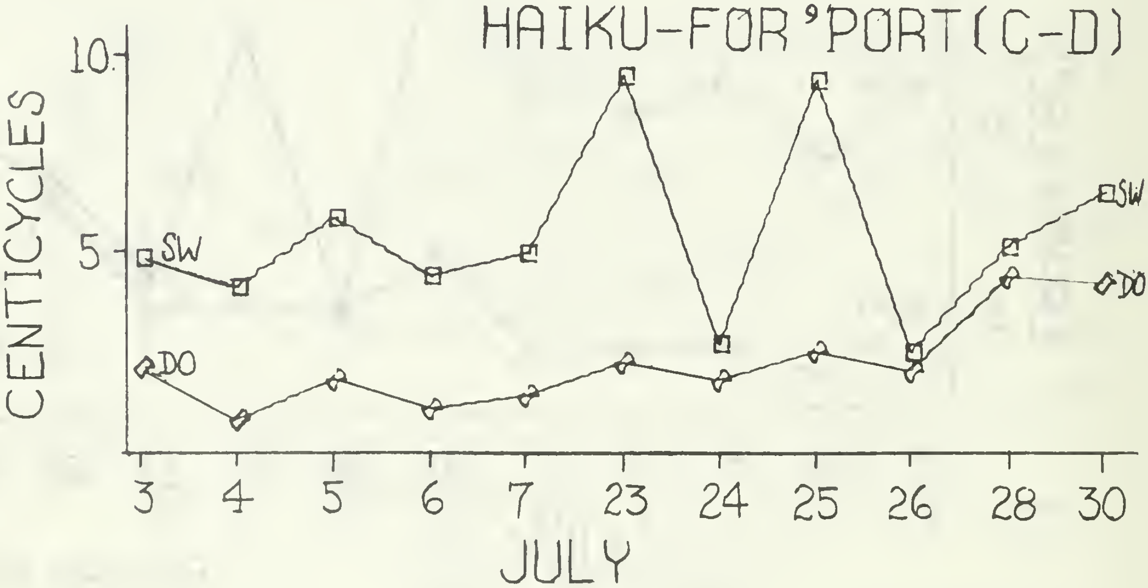
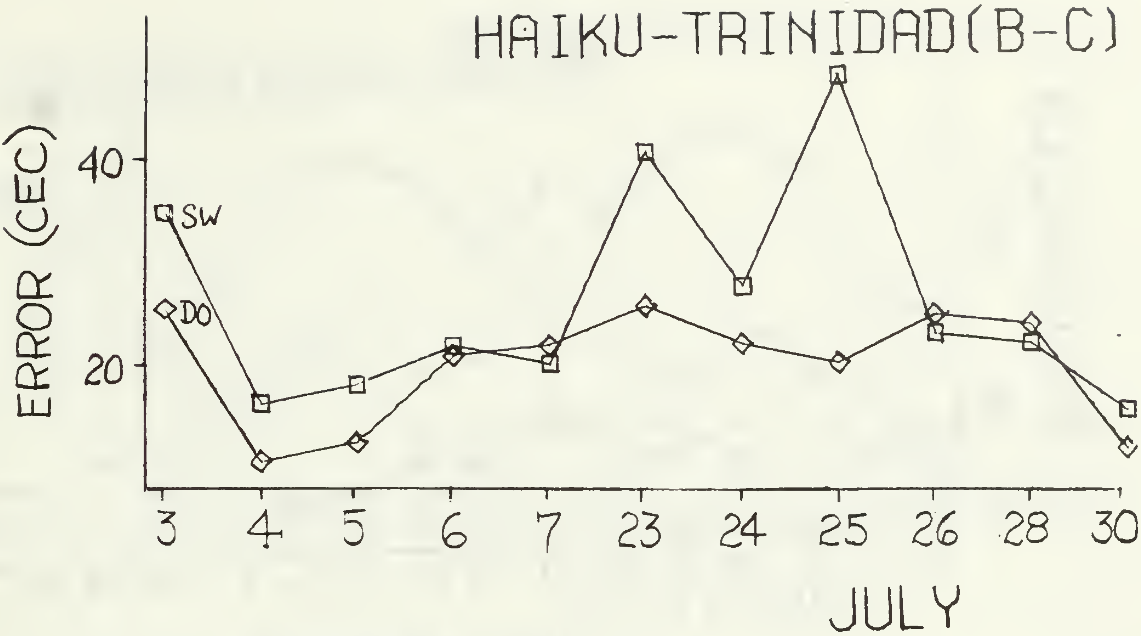


FIGURE 65



SITE PIGEON POINT

COMPARISON DIF OMEGA VS SKYWAVE

MAXIMUM ERROR 10.2 KHZ

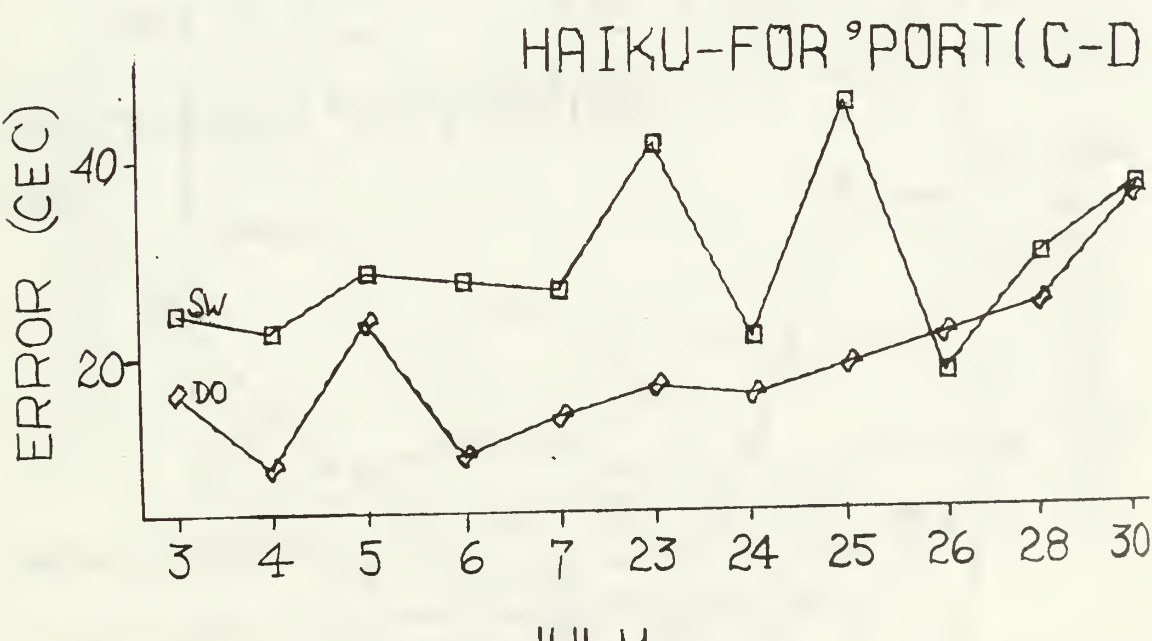


FIGURE 66

COMPARISON DIF OMEGA VS SKYWAVE

CORRECTED AVERAGE ERROR

SITE POINT SUR 13.6 KHZ

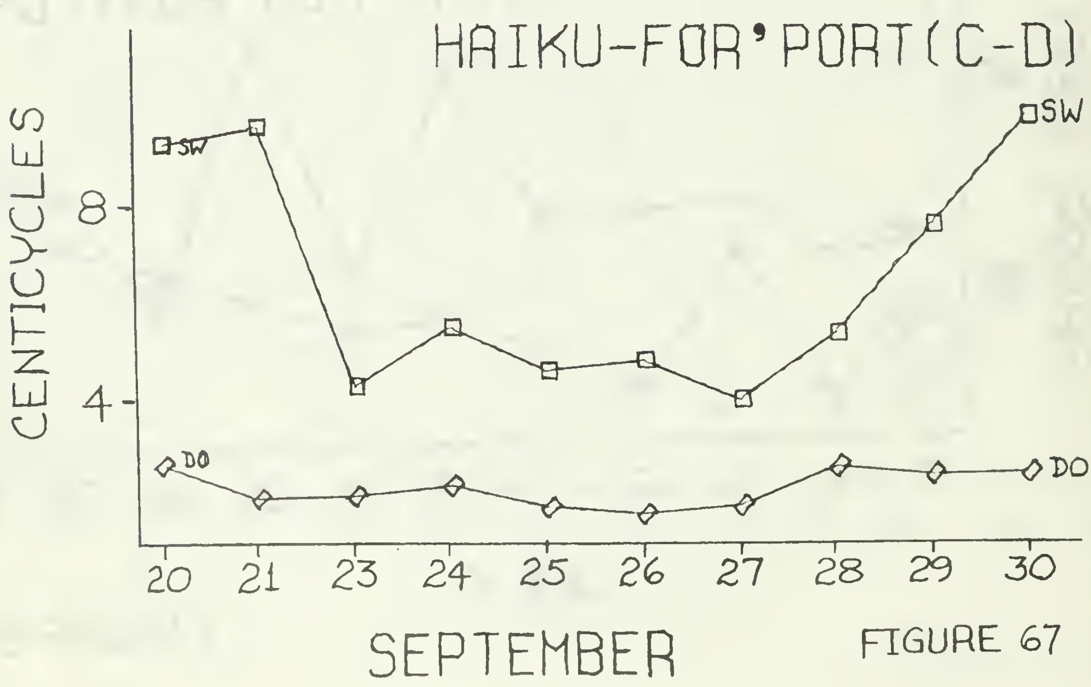
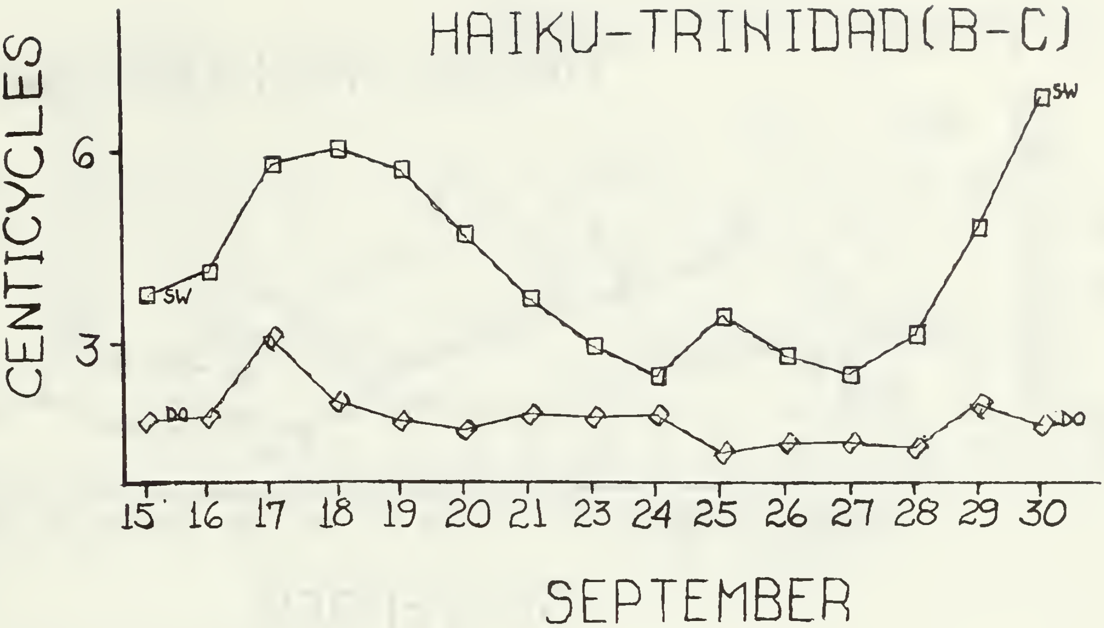


FIGURE 67



COMPARISON DIF OMEGA VS SKYWAVE

CORRECTED STANDARD DEVIATION

SITE POINT SUR 13.6 KHZ

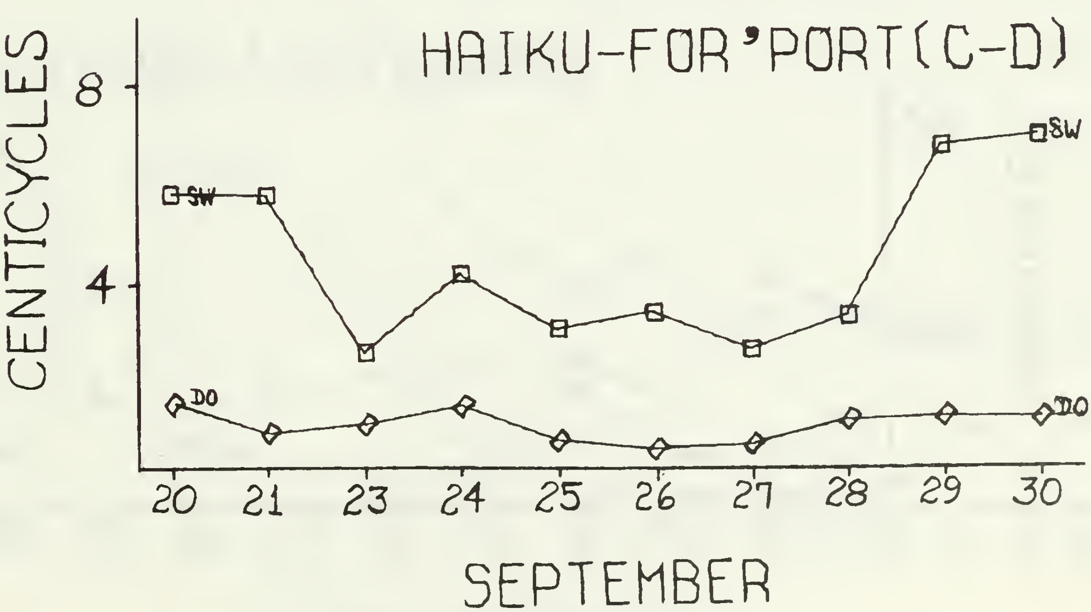
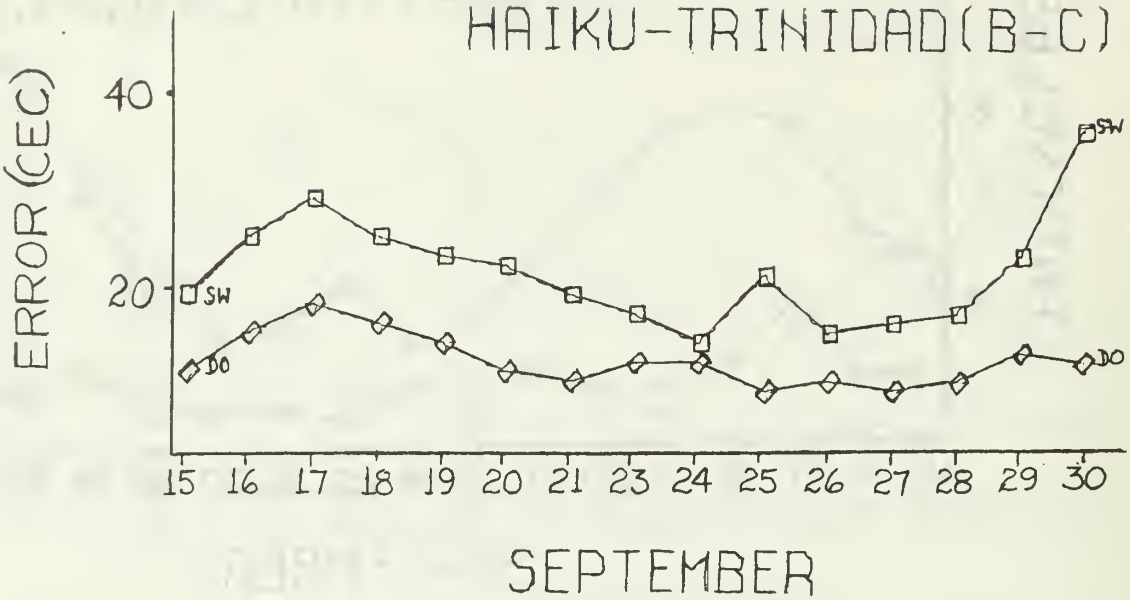


FIGURE 68



COMPARISON DIF OMEGA VS SKYWAVE

CORRECTED MAXIMUM ERROR

SITE POINT SUR 13.6 KHZ

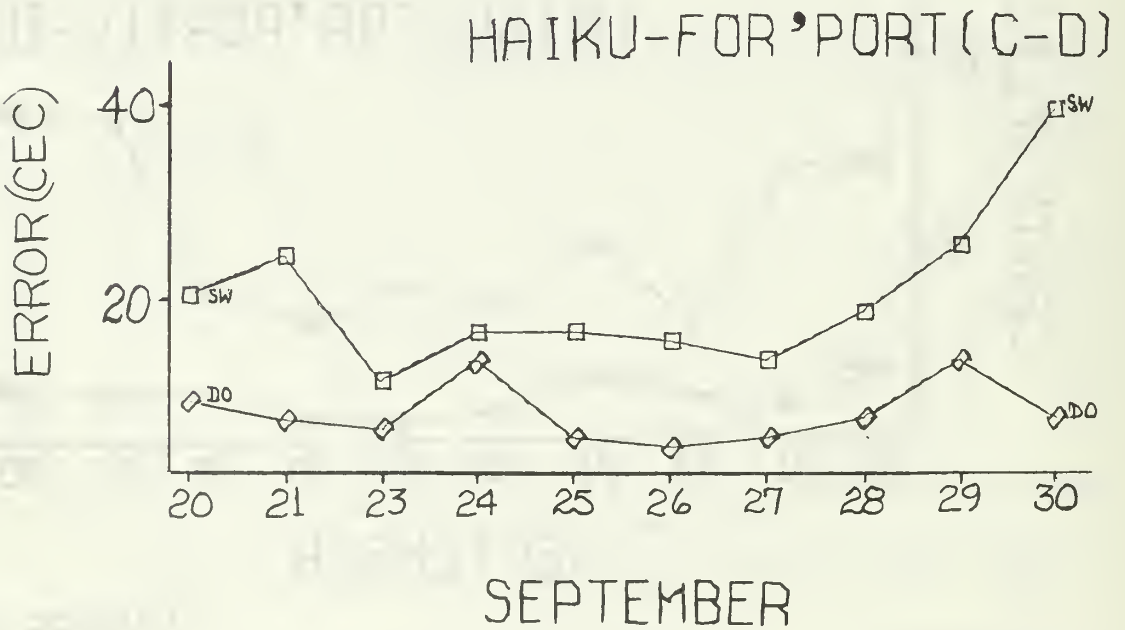
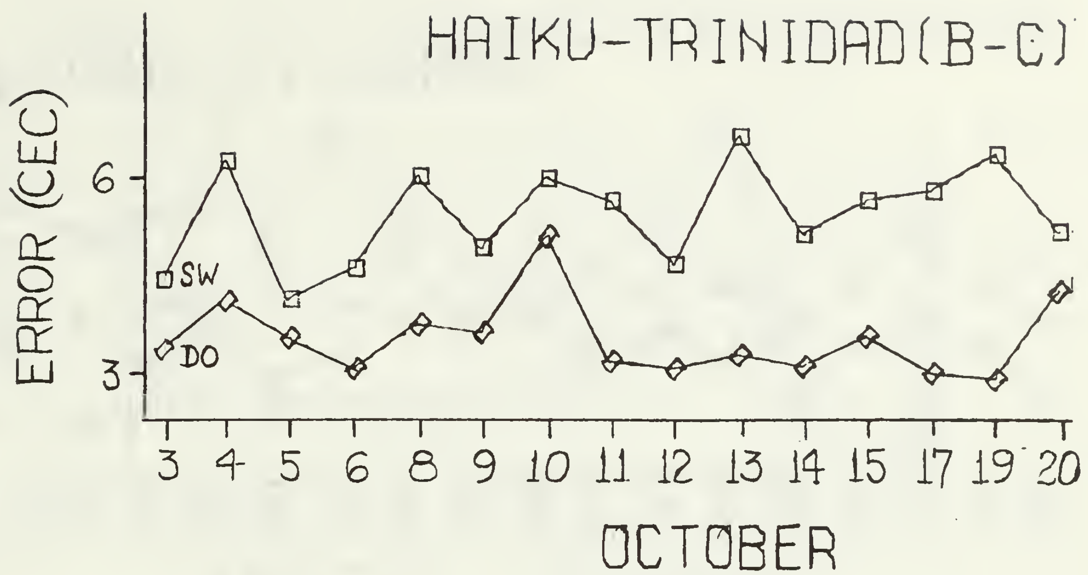


FIGURE 69



SITE POINT SUR

COMPARISON DIF OMEGA VS SKYWAVE

CORRECTED AVERAGE ERROR 10.2

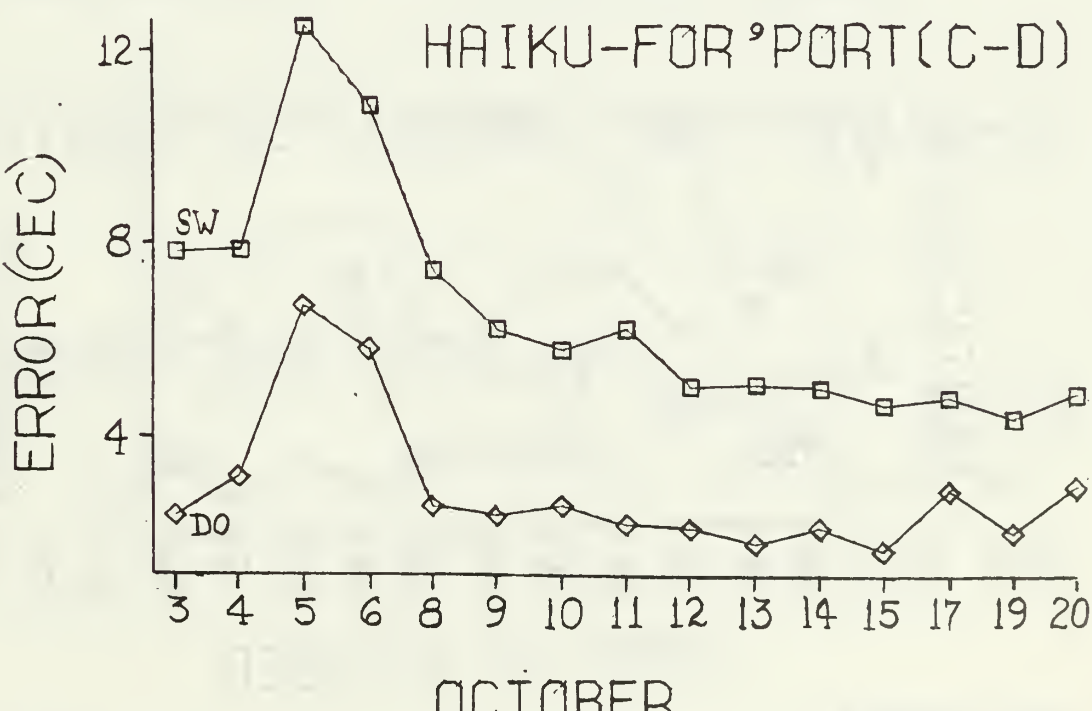
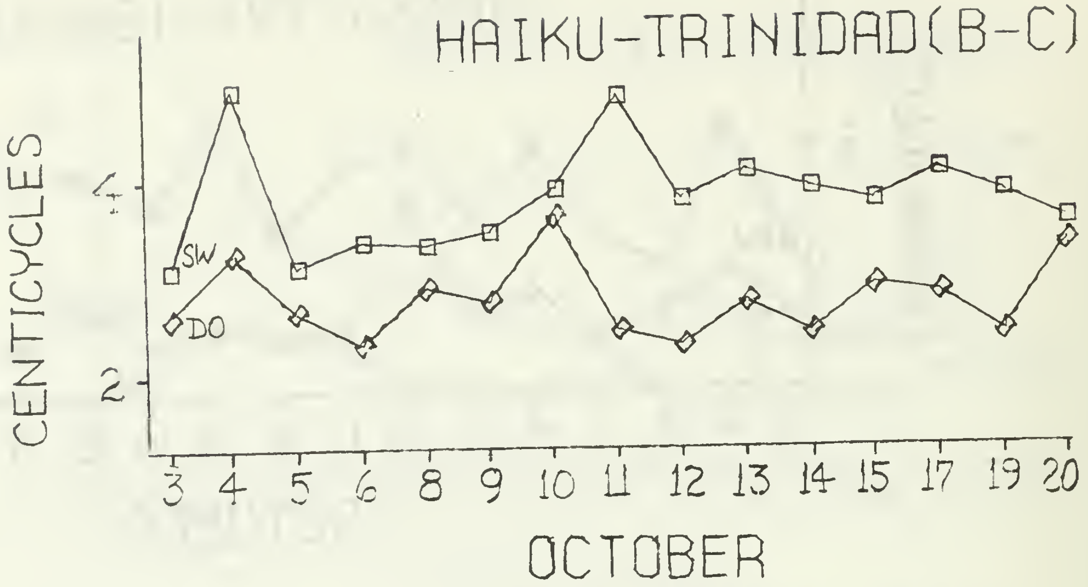


FIGURE 70



SITE POINT SUR 10.2 KHZ

COMPARISON DIF OMEGA VS SKYWAVE

CORRECTED STANDARD DEVIATION

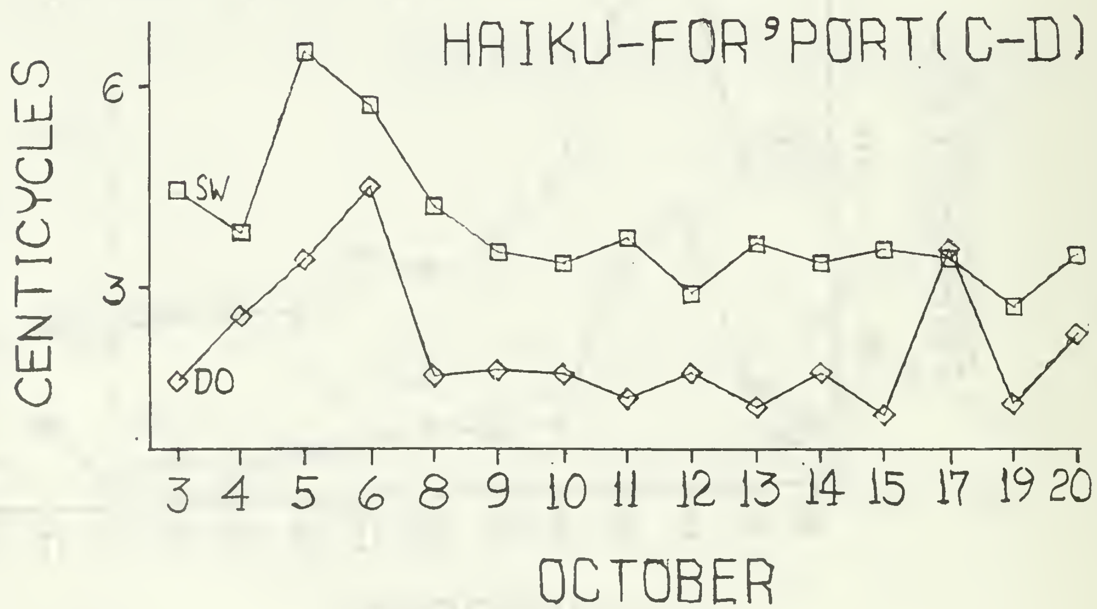
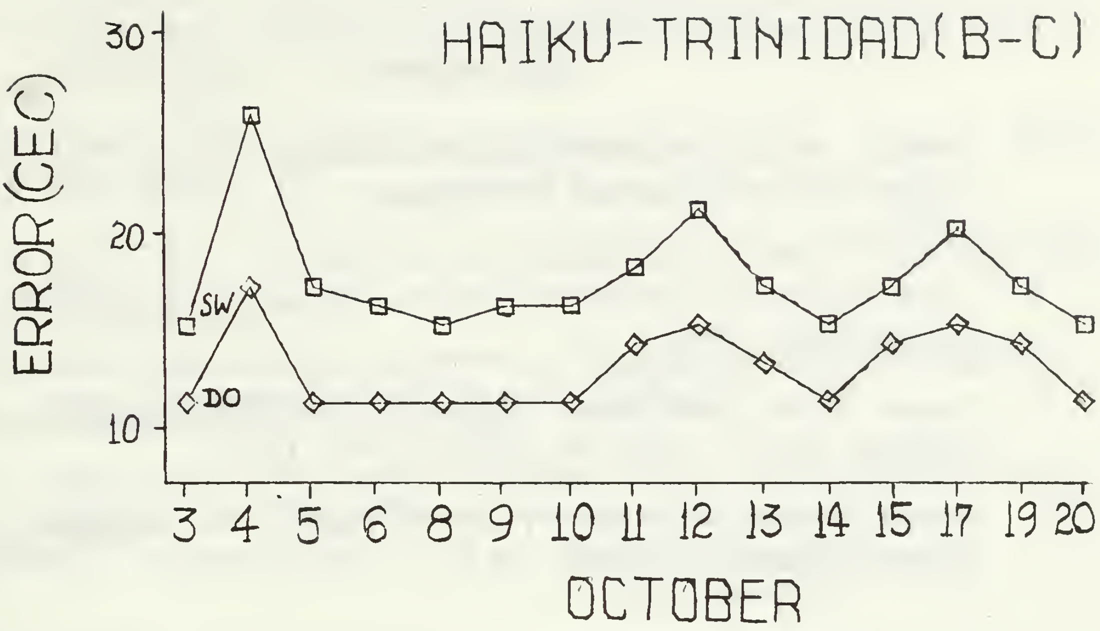


FIGURE 71



SITE POINT SUR 10.2 KHZ

COMPARISON DIF OMEGA VS SKYWAVE

CORRECTED MAXIMUM ERROR

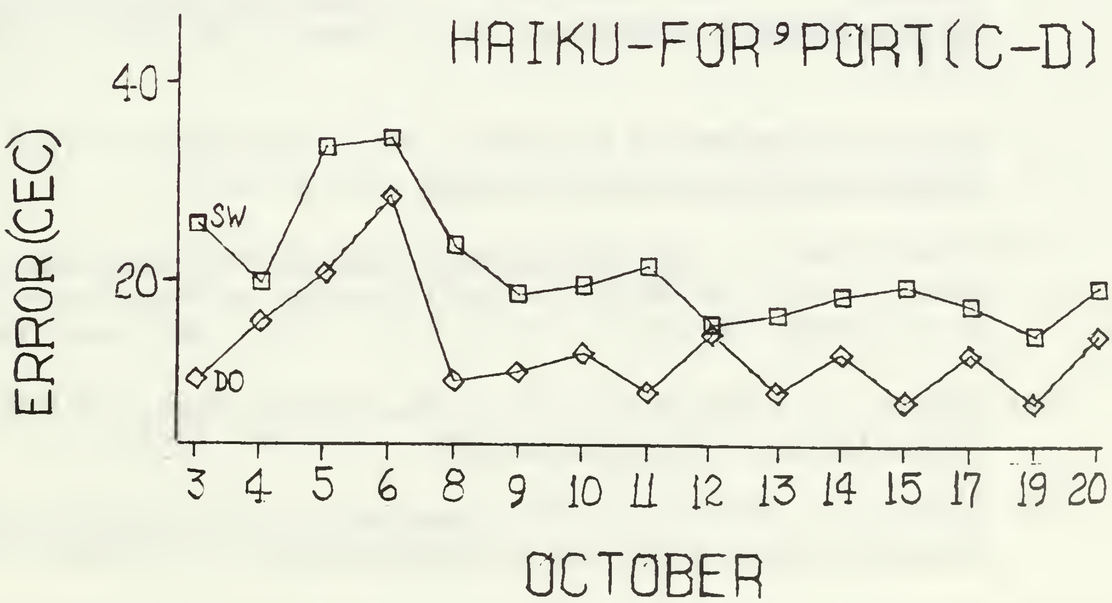


FIGURE 72

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13. ABSTRACT

Omega is a long range electronic navigation system which utilizes phase difference measurements between signals received from two transmitting stations to determine a line of position. The major cause of inaccuracy in the system is the propagation anomalies of the Omega signals. Differential Omega is based on the theory that throughout a small geographical region the phase difference errors caused by these anomalies are identical. A monitor site might be established within this area which would determine the extent of the error and relay this information to other users. It is the purpose of this thesis to present and test a workable Differential Omega system which utilizes a Coast Guard radiobeacon as a monitor site and the modulated radiobeacon signal to transmit the correction information.

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A-31408

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Differential Omega System						
Omega						
Electronic Navigation						
VLF Navigation						
VLF Phase Measurements						
Coast Guard Radiobeacon						
VLF Propagation						